THE INFLUENCE OF DIRECT CYLINDER INJECTION OF ETHYL ALCOHOL AND WATER ON DETONATION

R. M. DOUGHERTY
B. M. ROBINSON
J. W. SHUFF
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ETHYL ALCOHOL AND WATER
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Thesis
D68

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

We herewith submit a thesis entitled "The Influence of Direct Cylinder Injection of Ethyl Alcohol and Water on Detonation." This is in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

ACKNOWLEDGEMENTS

The authors wish to express their grateful appreciation for the assistance willingly rendered by the entire staff of the Sloan Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts. We are particularly indebted to Professor C. F. Taylor, Professor E. S. Taylor, Associate Professor A. R. Rogowski, Assistant Professor W. A. Leary, Assistant Professor P. M. Ku, and Messrs. C. Kano, J. L. Fardy, and E. Gugger for their generous and capable guidance during the course of this investigation.

TABLE OF CONTENTS

I - SUMMARY

Tests were run at the Sloane Laboratory, Massachusetts Institute of Technology, to compare the relative effect of injecting ethyl alcohol and distilled water directly into the cylinder of an internal combustion engine for the purpose of suppressing detonation. The investigation was confined to the cruising range and the following general results were evident:

(1) A marked increase in detonation limited IMEP is realized for alcohol/fuel ratios up to 0.8 with the engine operating at fixed compression ratio, RPM and F/A ratio. For purposes of comparison at a water/fuel ratio of 0.5, a fuel/air ratio of .07, and a compression ratio of 7.0, a 15% increase in detonation limited IMEP is obtained with water injection and an additional 20% boost in detonation limited IMEP may be obtained with alcohol injection.

(2) In all cases it is possible to obtain increasing values of detonation limited IMEP with increasing alcohol/fuel or water/fuel ratios, although the benefit is less pronounced above fluid/fuel ratios about 0.8.

(3) In the region of lower fluid/fuel ratios (up to 0.7) the injection of alcohol increases the indicated thermal efficiency up to 3%, whereas the injection of water has a slight tendency to decrease it. These efficiencies are based on the heating value of the fuel alone.

(4) If operating at a constant detonation limited IMEP, a given compression ratio may be utilized at an appreciably lower alcohol/fuel ratio as compared to the water/fuel ratio required to obtain the same condition. This effect is more pronounced at higher fuel/air ratios and enables the designer to take advantage of the increase in thermal efficiency associated with higher compression ratios.

(5) At a fixed fuel/air ratio and fluid/fuel ratio the detonation limited IMEP varies inversely with the compression ratio.

(6) In going from a fuel/air ratio of .06 and .08 at a fixed compression ratio, the relative effect of enrichening the mixture with fuel is more beneficial towards raising the detonation limited IMEP than is the injection of water; i.e., a given weight of fuel addition to the mixture allows a higher detonation-free IMEP than does the injection of an equal weight of water. The injection of alcohol, however, is slightly more effective than enrichening the fuel/air ratio.

II - INTRODUCTION

The purpose of this investigation is to compare the effects of direct cylinder injection of ethyl alcohol and distilled water as a means of suppressing detonation; these fluids were injected separately and not as a mixture.

To date little work has been done in exploring the field of direct cylinder injection to suppress detonation, as compared to injection into the manifold. However, with the great improvement of cylinder injection equipment in recent years, due to efforts in the line of direct fuel injection, the practicability of injecting an anti-detonating agent directly into the last part of the charge to burn has been increased. Previous work has centered chiefly on the use of water and alcohol injection to extend the allowable maximum power ratings of an engine, whereas this report investigates the increase in allowable cruising IMEP made possible by cylinder injection. For this purpose it was decided to use only unsupercharged inlet pressures, and hence it was necessary to use 73 octane gasoline as fuel, so that detonation could be readily encountered at a compression ratio as low as 6.0. Likewise the practical cruising range of fuel/air ratios from .06 to .08 was chosen, and a currently achievable range of compression ratios from 6.0 to 8.0.

Interest in ethyl alcohol as a fluid to be injected is due largely to its having a heating value in itself, and to its having a

high anti-knock rating when used as a primary fuel. Interest in water stems from its universal availability and its high latent heat of vaporization.

III - DESCRIPTION OF APPARATUS

A schematic arrangement of the entire apparatus appears in Figure 19.

The engine used in this investigation is a standard CFR test engine made by the Waukesha Motor Company, Waukesha, Wisconsin; it has a displacement volume of 37.33 cu. in., with a 3.25 in. bore and a 4.50 in. stroke.

The induction system consists of an inlet from either the atmosphere or a supercharged pressure line, a .515 Foxboro orifice to measure the air flow, a surge tank, mixing tank with steam jacket heater, a throttle valve, and necessary piping. The surge tank is provided to dampen any oscillations in the line due to the intermittent pumping action of the engine, and the mixing tank is designed to thoroughly vaporize the fuel and create a uniform mixture. The mass flow of air is measured by a differential water manometer placed across the orifice, and fuel is injected under 23 psi pressure into the top of the mixing tank; its mass rate of flow is measured by means of a Fischer & Porter rotometer. Inlet pressure is measured by a differential mercury manometer, one leg of which is vented to the atmosphere and the other to the mixing tank, while inlet temperature is measured by a mercury bulb thermometer inserted in the inlet manifold. The above system enables accurate determination and control of inlet mixture conditions.

The engine speed is controlled by varying the field resistance in a D.C. dynamometer (see Figure 20), which is run directly from the engine crankshaft. A rough indication of the speed may be read on a tachometer driven by a flexible cable, and the precise engine RPM may be set for integral multiples of 100 by a stroboscope flashing with line frequency (60 cps) upon the flywheel, which has 36 radial lines inscribed; under stroboscopic light these lines appear stationary when the engine is running at an integral multiple of 100 RPM.

The dynamometer has a torque arm attached to its field casing, and the torque arm actuates a piston; this latter transmits hydraulic pressure through a medium of 50% SAE 20 oil and 50% kerosene to the bottom of a column of mercury, the height of which above or below a fixed zero setting can be converted to BMEP or FMEP respectively.

The cylinder jacket temperature is controlled by varying the rate of flow of cooling water through the jacket condenser. Likewise the exhaust jacket is kept cool by the continual flow of water. Both steam and water may be fed to the oil temperature control jacket so as to maintain the oil temperature within narrow limits.

The special equipment used in this investigation consists of an American Bosch single piston, positive displacement injection pump number APE 1B 70P 300 3 X58201 (see Figure 16). With increasing

volume flow this pump advances the initial angle of injection, while the final angle remains constant for all flow rates. In conjunction with this pump a Bendix injection nozzle, number 135026, was inserted in the cylinder opposite the spark plug; it is an early experimental model of which only 30 were made, but it furnished satisfactory spray characteristics and differs but slightly from current production models. The nozzle release pressure, chosen as 500 psi to give the best spray, may readily be set by adjusting and securing the spring tension within the nozzle. The pump will develop up to 20,000 psi pressure, so that there is an ample margin of pressure to ensure nozzle ejection. A pressure head of 6 feet of water feeds the pump from a float chamber employed to keep this head constant. Volume flow of fluid through the pump is controlled by means of a micrometer adjustment on the pump housing; this flow is measured by a rotometer located between the float chamber and the pump, and a thermometer is set in the outlet from the rotometer to read the fluid temperature. The arrangement is shown in Figure 18.

A magnetic dp/dt pick-up is inserted into the cylinder in one of the extra spark plug holes, and the voltage signal from the pick-up is fed to a cathode ray oscilloscope to form a characteristic pattern on the screen. When a blip, due to a very rapid change of pressure in the cylinder, appears on the characteristic screen pattern, it is an indication of incipient detonation. This is a more accurate method of

determining the point of incipient detonation than the magneto-striction or bouncing pin methods.

IV - PRELIMINARY PROCEDURE

The following preliminary operations were necessary to set up the apparatus in order to obtain the desired test data.

First a manometer board (Figure 17) was constructed to measure inlet pressure, static pressure drop across the air intake orifice, exhaust pressure, and brake load. Secondly there had to be constructed a water and alcohol feed system, consisting of a 3 gallon bottle and float chamber suspended from an overhead beam so as to provide a steady 6 foot gravity feed to the injection pump. This system is shown in Figure 17.

The fuel rotometer was calibrated at a fuel temperature of 78°F by using a standard calibration set, which enables the accurate determination of a time interval during which a given mass of fluid flows through the rotometer; from this information the rate of flow may be calculated, corresponding to the observed scale reading on the rotometer. In a like manner a second rotometer was calibrated separately for both water and alcohol, and in the case of water the calibration was run at 3 different temperatures by causing the water to flow through a heat exchanger prior to entering the rotometer. This latter showed that a change in temperature of 4°F caused an error in mass flow of slightly less than 4%, and throughout the later test runs the fluid temperatures were observed and found to vary less than 2°F from the calibration temperature of 77°F; this was due to the fact that

the fluid was allowed to achieve room temperature before being used, and room temperature varied within a narrow range. In subsequent test runs interpolation for temperature was employed when necessary.

A great deal of difficulty was experienced in determining the best combination of Bosch injection pump and injection nozzle. The spray from the nozzle was observed by means of a stroboscope connected to the set of ordinarily used breaker points, which fire every other revolution of the crankshaft; since the pump is driven directly by the camshaft the stroboscope frequency was identical to the frequency of nozzle ejection, and hence the spray appeared stationary when viewed under stroboscopic light. The first pump that was installed produced a constant initial angle of injection and variable final angle, as the volume flow through the pump was changed, but this pump gave an intermittent spray and had to be abandoned in favor of a newer pump, which had the characteristic of producing a variable initial and fixed final angle of injection. The latter pump provided a regular spray and was tested with several types of injection nozzles at various spring tension loadings, which were adjusted by a compression nut in the nozzle and checked for release pressure in a hand operated hydraulic pump with a bourdon tube gage attached. A Bendix injection nozzle with spring loading of 500 psi was finally selected as giving the most desirable spray. The tubing between the

pump and nozzle was made as short as possible and with a minimum number of bends; in addition the system was frequently and thoroughly bled of air by means of 2 bleed jets on the pump housing and by loosening the tube joint at the pump. Care was taken to make certain that the injection occurred on the compression stroke by observing under stroboscopic light the opening and closing of the inlet valve.

The effect on initial injection angle of varying the mass flow through the pump was determined by observing the spray under stroboscopic light flashing at half crankshaft frequency; the timing of the stroboscope flashes was varied by rotating the breaker point housing until the spray was at the point of disappearing up into the nozzle, thus indicating the start of nozzle ejections; then the stroboscope was made to illuminate the spark disc and indicate the angle of initial injection as that at which the top center mark appeared on the protractor scale around the spark disc. In a similar manner the angle of final injection was determined and found to be invariant with volume flow, whereas the angle of initial injection advanced in a linear fashion with increased flow rate, as shown in Figure 9. The optimum coupling angle between pump and camshaft was determined by making runs of detonation limited IMEP vs. water/fuel ratio at 3 different coupling angles; the optimum angle was that giving the highest limiting IMEP, as shown in Figure 10.

In order to test the induction system for leaks, a gage pres-

sure of 10 psi was applied and a soapy solution painted on all joints; a few minor leaks were evident and were stopped by painting the defective joint with glyptol. As a final check on the induction system a run was made of brake load vs. F/A ratio; the peak occurred at F/A=.075, thus constituting a satisfactory final check.

The micrometer for setting the compression ratio was checked by running the engine until normal operating temperatures were reached and then, with the piston on top center, measuring the weight of distilled water required to fill the cylinder up to the thread corresponding to the depth of the injection nozzle; the volume corresponding to this weight of water is equal to the clearance volume, which was checked against the correct value as taken from a table of standard CFR clearance volumes vs. micrometer setting. The final check on the engine consisted of setting the correct valve clearances and spark plug gap.

V - OPERATING PROCEDURE

The standard starting procedure (appendix) was used to start the engine which was then allowed to warm up for at least an hour, after which time equilibrium conditions had become established. During the warm-up period the following operating variables were set at their prearranged values: inlet temperature 140°F, oil temperature 140°F, cylinder jacket temperature 210°F, and engine speed 1300 RPM.

Since the Bosch injection pump was designed for use with diesel oil rather than alcohol or water, an auxiliary feed of diesel oil was supplied to the pump during the above warm-up period, thus providing lubrication for the finely lapped piston. In addition, diesel fluid was circulated through the pump after every hour of operation on alcohol or water, as well as at the conclusion of each day's runs.

Following the warm-up period the injection pump was shut off, and the sylphon bellows, which dampen the oscillations due to intermittent pumping and produce a steady flow of fluid through the rotometer, were drained of diesel oil and filled with alcohol or water as desired. In this operation care was taken that the bellows were not allowed to expand too rapidly and cause a flow rate high enough so as to cause air to get into the system at the float chamber. Then the pump was set at a moderate flow and time allowed for all diesel oil to

be flushed through the injection system; during this period the pump was thoroughly bled of any air that might have been in the lines or pump. The satisfactory performance of the entire injection system was manifested by a steady rotometer reading.

When the desired compression ratio had been set, the following sequence of operations proved to be most efficacious and was used on all but the first few runs: while injecting excess fluid to prevent detonation, the throttle was fully opened so that inlet pressure was slightly less than atmospheric; then the fuel flow was adjusted to give the desired F/A ratio, and after allowing several minutes for the mixture to become adjusted, the amount of injected anti-knock fluid was gradually reduced until incipient detonation was indicated on the cathode ray oscilloscope. After recording all data for the run, the inlet pressure was decreased to a predetermined value and the fuel flow again adjusted to maintain the same F/A ratio; the quantity of fluid was then decreased until a second point of incipient detonation was reached, and data was recorded. In a like manner points of incipient detonation were determined until the flow of injected fluid became zero, and then the process was repeated at a different value of F/A ratio or compression ratio.

VI - DISCUSSION

In order to best show the relative effectiveness of injecting 95% ethyl alcohol and water directly into the cylinder for the purpose of suppressing detonation, Fugures 1, 2 and 3 picture detonation limited IMEP plotted against alcohol/fuel or water/fuel ratio required to enable the use of a given detonation-free IMEP; these curves are for each of three compression ratios, 6, 7 and 8. The primary variables on each curve are inlet pressure and alcohol or water flow rate, while a secondary variable is the initial injection angle which advances with increasing fluid flow due to the inherent characteristic of the injection pump; all other variables, F/A ratio, compression ratio, spark advance, RPM, inlet temperature, and jacket temperature are held constant along a given curve. Proceeding up one of these curves from left to right successive points represent higher inlet pressures, and give the maximum detonation-free IMEP that can be obtained using the corresponding flow of anti-detonating fluid. The spread of points on all these curves is well within experimental limits, and several check runs were made to substantiate data taken on a previous day, thus indicating satisfactory control throughout the tests.

These figures show a distinctive S-curve that is representative of the alcohol in suppressing detonation; this trend is especially evident at compression ratios of 7 and 8, while at a compression ratio of 6 the use of unsupercharged inlet pressures limited the

alcohol/fuel ratio to a lower range than that needed to suppress detonation at higher compression ratios. The water curves increase in an approximately linear manner up to high flow rates where there is evidence of an upward trend, indicating an increased effectiveness in raising the allowable IMEP.

In all cases the injection of an additional weight of fluid allows the use of a higher IMEP, but the use of alcohol offers a vast advantage over water in that at the same fluid flow rate a much higher IMEP may be attained. This may be explained by the greater effectiveness of alcohol in altering the pressure-temperature-time combination leading to auto-ignition of the end gas, and this relation can be changed by altering the chemical composition of the unburned gases, or by a catalytic effect on the reaction, or more simply by evaporative cooling of the end gases. Alcohol has a lower viscosity than water and hence finer droplets are formed; in combination with this its higher rate of evaporation causes a more profound cooling effect upon the gases. In addition there is undoubtedly a greater chemical effect in the case of alcohol, which itself has a heating value and a rather high anti-knock rating. The injection of both fluids increases the number of mols of gas in the cylinder, and hence would tend to raise the pressure on the piston during the power stroke if the cooling effect were not sufficient to overcome this rise in pressure. In the region of low flow rates the great increase in IMEP is attributable to both evaporative cooling and to the combustion of part of the

alcohol; in this range the initial injection of the fluid occurs around 20-40°ATC, so that the adiabatic compression pressures in the cylinder are not lowered during most of the peak pressure region of the P-V diagram. At higher flow rates the initial angle of injection is advanced until at very high flows the injection is coincident with the spark, thus causing a profound cooling of the cylinder gases.

Figures 4, 5 and 6 represent lines of constant ISLC plotted on curves identical with 1, 2 and 3 for the range of fluid/fuel ratio from 0-1.0, which represents the only region that could possibly be considered as having any practical importance. The term liquid is here used to include both fuel plus anti-detonating fluid, and the curves indicate that for a given value of ISLC the injection of additional water rêsults in a lower IMEP in all cases, thus giving positive evidence against its being practical. However, the positive slope of constant ISLC lines in the low region of alcohol/fuel ratio (below 0.4) indicates that for a given liquid consumption a higher detonation-free IMEP may be realized by injecting alcohol into the last part of the charge to burn, and hence its use is of considerable interest. At alcohol/fuel ratios above 0.4 the slope of the ISLC lines becomes negative, and the practicability of alcohol injection disappears in this upper region. The above statements refer in particular to compression ratios 6 and 7; at compression ratio 8 the slope becomes horizontal in the low range and little benefit is derived for cruising conditions.

Figure 7 represents a curve of detonation limited compression ratio vs. fluid/fuel ratio for the condition of constant IMEP=100 psia. This curve, as well as Figures 4, 5 and 6, is a cross-plot made from Figures 1, 2 and 3, and it indicates that in order to operate at a fixed IMEP more fluid must be injected at the higher compression ratios; this is to be expected, but it is interesting to note the vast superiority of alcohol over water for this purpose. Here the region of practical interest is that of higher F/A ratios, where the returns from injecting a small amount of alcohol are most pronounced.

Figure 8 shows a curve of indicated thermal efficiency vs. fluid/fuel ratio for 3 F/A ratios at compression ratio 7. The efficiencies are based on the heating value of the fuel alone, since the prime purpose of injecting the alcohol is as an anti-detonating agent rather than a fuel, and water, used for the same purpose, has no heating value. The water gives a slightly decreased thermal efficiency, whereas for alcohol/fuel ratios up to 0.7 the efficiency rises; the greatest increase is 3% at F/A=.06, and may be explained by the excess oxygen being available to burn the alcohol. As a primary combustion process this occurs too late in the power stroke to be highly efficient in itself, but it does, however, add a slight increment of pressure to raise the IMEP. In the case of water the decrease in thermal efficiency is caused by lowering the adiabatic compression pressure of the end gases in the cylinder.

VII - CONCLUSIONS

As a result of this investigation the following conclusions are reached:

(1) At all F/A ratios and compression ratios the injection of ethyl alcohol is vastly superior to the use of water. In the useful range of fluid/fuel ratios (below 0.5) the injection of alcohol results in as much as a 40% increase in the detonation limited IMEP over that which could be obtained with no anti-detonating fluid. At the same fluid/fuel ratio in the case of water a 20% increase is obtained. As the fluid/fuel ratio increases these percentage gains increase, but at the expense of prohibitively high flow rate for extended operation.

(2) At a constant (and low) ISLC in the case of alcohol a higher IMEP may be obtained with using a low F/A ratio. However, with water injection and constant ISLC it is necessary to use a high F/A ratio to obtain the optimum detonation-free IMEP.

(3) At fluid/fuel ratios below 0.5 a slightly higher IMEP is obtainable by injecting a given weight of alcohol than by adding the same weight of fuel to the mixture, whereas low rates of water flow are not as effective as enrichening the mixture with additional fuel within the range of cruising F/A ratios herein investigated.

(4) The injection of alcohol is highly effective in raising the allowable compression ratio in order to take advantage of higher thermal efficiency.

(5) In order to operate at a given IMEP a lower octane fuel can be used in conjunction with direct cylinder injection of alcohol or water, with the former being more effective.

(6) The difficulties introducd by the installation, timing, and maintenance of an injection pump and nozzle, together with auxiliary supply, might easily overshadow the aforementioned advantages associated with direct cylinder injection. This would be especially true for a multi-cylinder installation.

(7) Some of the complications of a direct injection system could be obviated by using gasoline both as primary fuel and antidetonating fluid (see appendix XII-a).

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IX - NOMENCLATURE AND FORMULAE

Symbols:

Pa	-	Corrected barometric pressure (in. Hg.)
Ta	-	Atmospheric temperature (°R)
Pe	-	Exhaust pressure (in. H_2O)
Pi	-	Inlet pressure (in. Hg.)
Ti	-	Inlet temperature (°F)
Ma	-	Mass rate of air flow (lbs/sec)
Wf	-	Mass rate of fuel flow (lbs/sec)
Ww	-	Mass rate of water flow (lbs/sec)
Wa	-	Mass rate of alcohol flow (lbs/sec)
B.L.	-	Brake load (in Hg.)
BMEP	-	Brake mean effective pressure (psia)
FMEP	-	Friction mean effective pressure (psia)
IMEP	-	Indicated mean effective pressure (psia)
IHP	-	Indicated horsepower.
ISLC	-	Indicated specific liquid consumption (lbs.liq/IHP hr.)
F/A	-	Fuel/air ratio.
S.A.	-	Spark advance (°BTC)
h	-	Orifice differential pressure (in. H_2O)
Vd	-	Displacement volume (cu.in.)

Formulae:

(a) $$Pa = 30 + \frac{\text{mm HG} - 762}{25.4} - \frac{\text{mm HG} \times T°C \times 6.4}{10^6}$$

(b) $$Ma = .01825 \times \left(\frac{Pa \times h}{Ta}\right)^{1/2}$$

(c) $$Wf = F/A \times Ma.$$

(d) $$BMEP = 4.245 \times B.L.$$

(e) $$FMEP = 4.245 \times F.L.$$

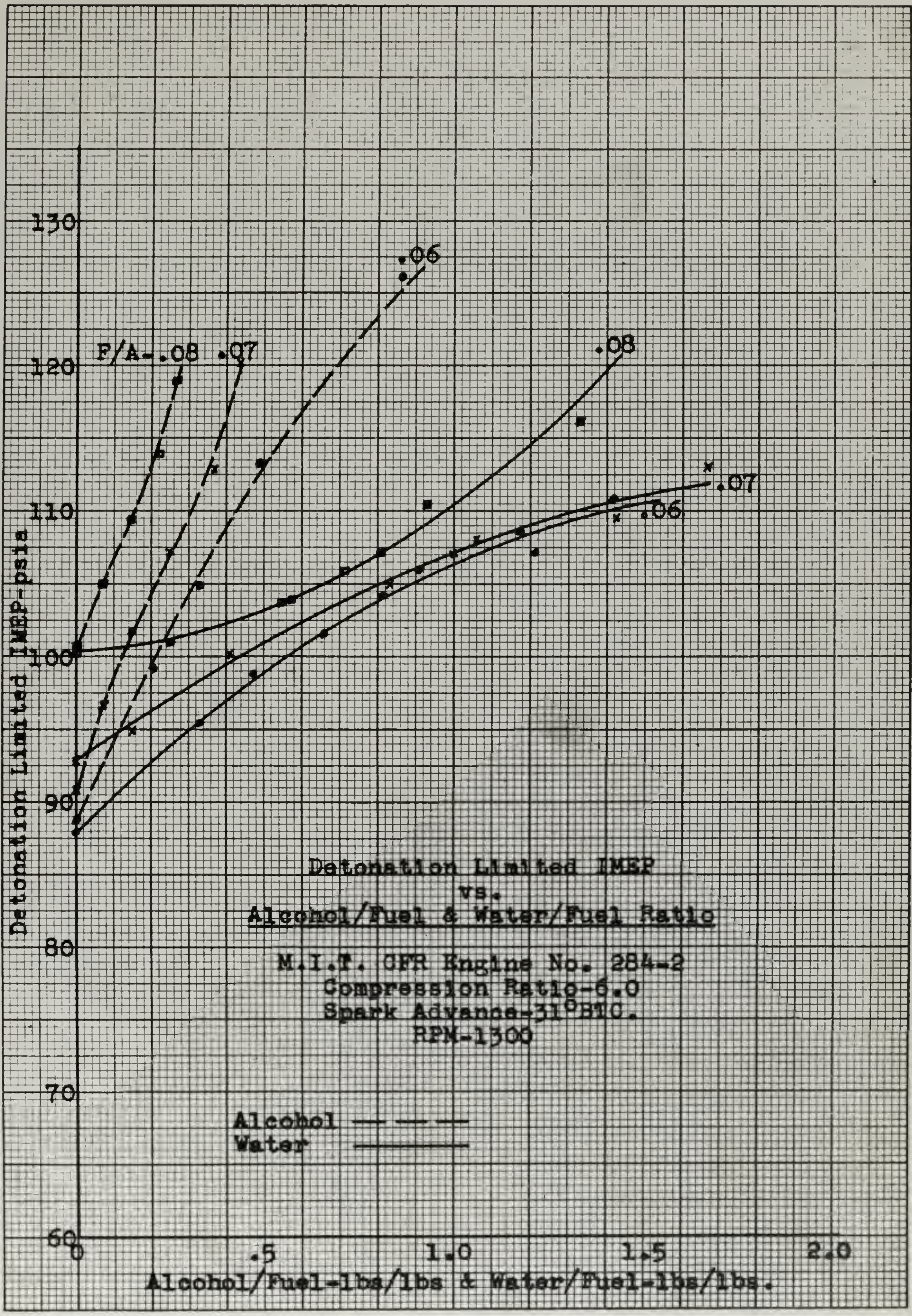
(f) $$IMEP = BMEP + FMEP.$$

(g) $$IHP = \frac{IMEP \times Vd \times RPM}{792{,}000} = .06125\ IMEP$$

(h) $$ISFC = \frac{WF \times 3600}{IHP}$$

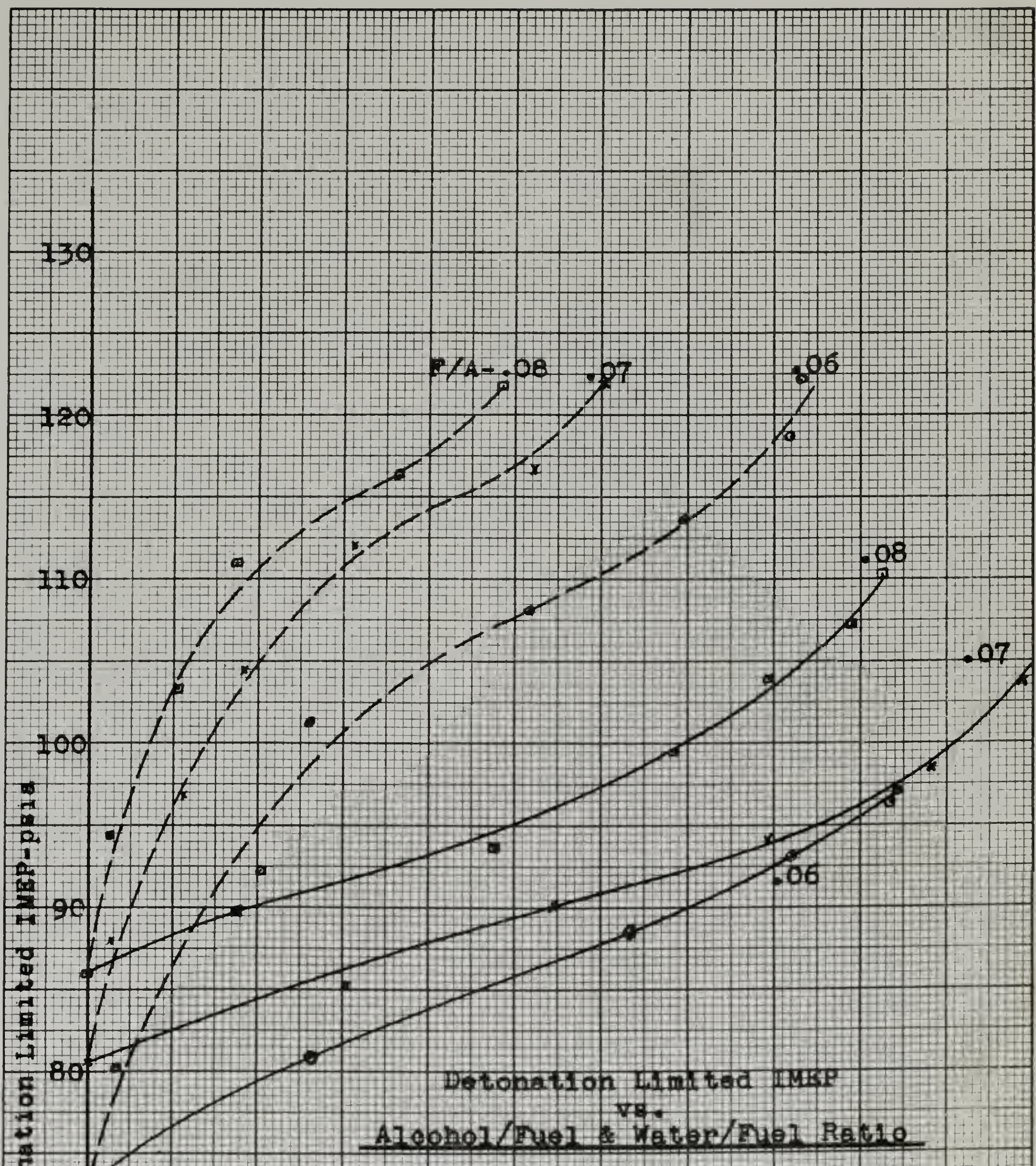
(i) $$ISLC = \frac{(Wf + Ww) \times 3600}{IHP}$$

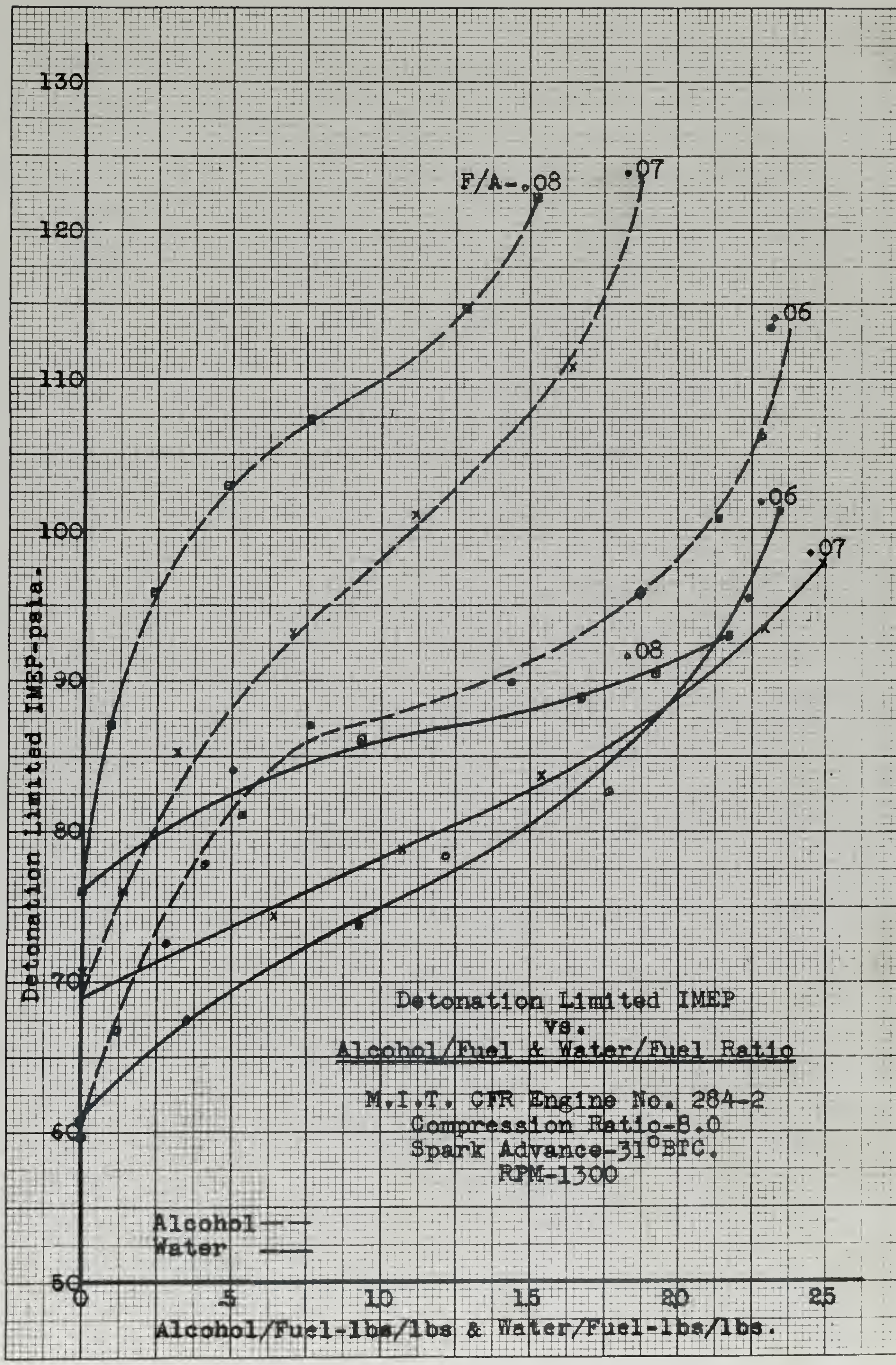
(j) $$i = \frac{2545}{ISFC \times 19{,}300}$$



Detonation Limited IMEP
vs.
Alcohol/Fuel & Water/Fuel Ratio
M.I.T. CFR Engine No. 284-2
Compression Ratio-6.0
Spark Advance-31°BTC.
RPM-1300
Alcohol
Water
F/A-.08
.07
.06
.08
.07
.06
Detonation Limited IMEP-psia
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs.
130
120
110
100
90
80
70
60
0
.5
1.0
1.5
2.0

Fig. 1


Detonation Limited IMEP vs. Alcohol/Fuel & Water/Fuel Ratio
M.I.T. CFR Engine No. 284-2
Compression Ratio-7.0
Spark Advance-31° BTC.
RPM-1300
Alcohol
Water
F/A-.08
.07
.06
.08
.07
.06
Detonation Limited IMEP-psia
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs.
60
70
80
90
100
110
120
130
0
.5
1.0
1.5
2.0



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80
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60
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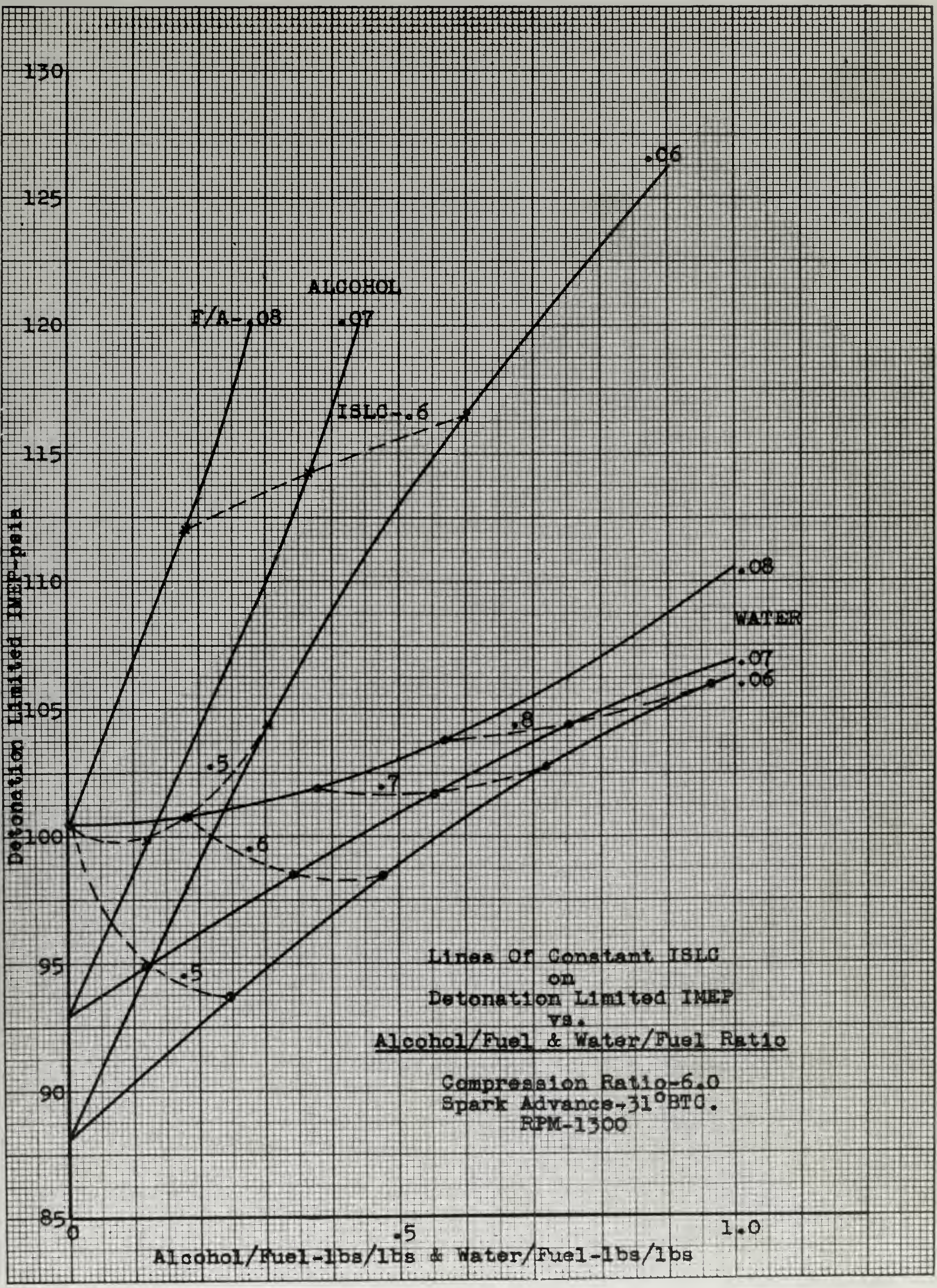
0
5
10
15
20
25
Detonation Limited IMEP-psia.
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs.
F/A-.08
.07
.06
.06
.07
.08
Detonation Limited IMEP
vs.
Alcohol/Fuel & Water/Fuel Ratio
M.I.T. CFR Engine No. 284-2
Compression Ratio-8.0
Spark Advance-31°BTC.
RPM-1300
Alcohol
Water

Fig. 3



130
125
120
115
110
105
100
95
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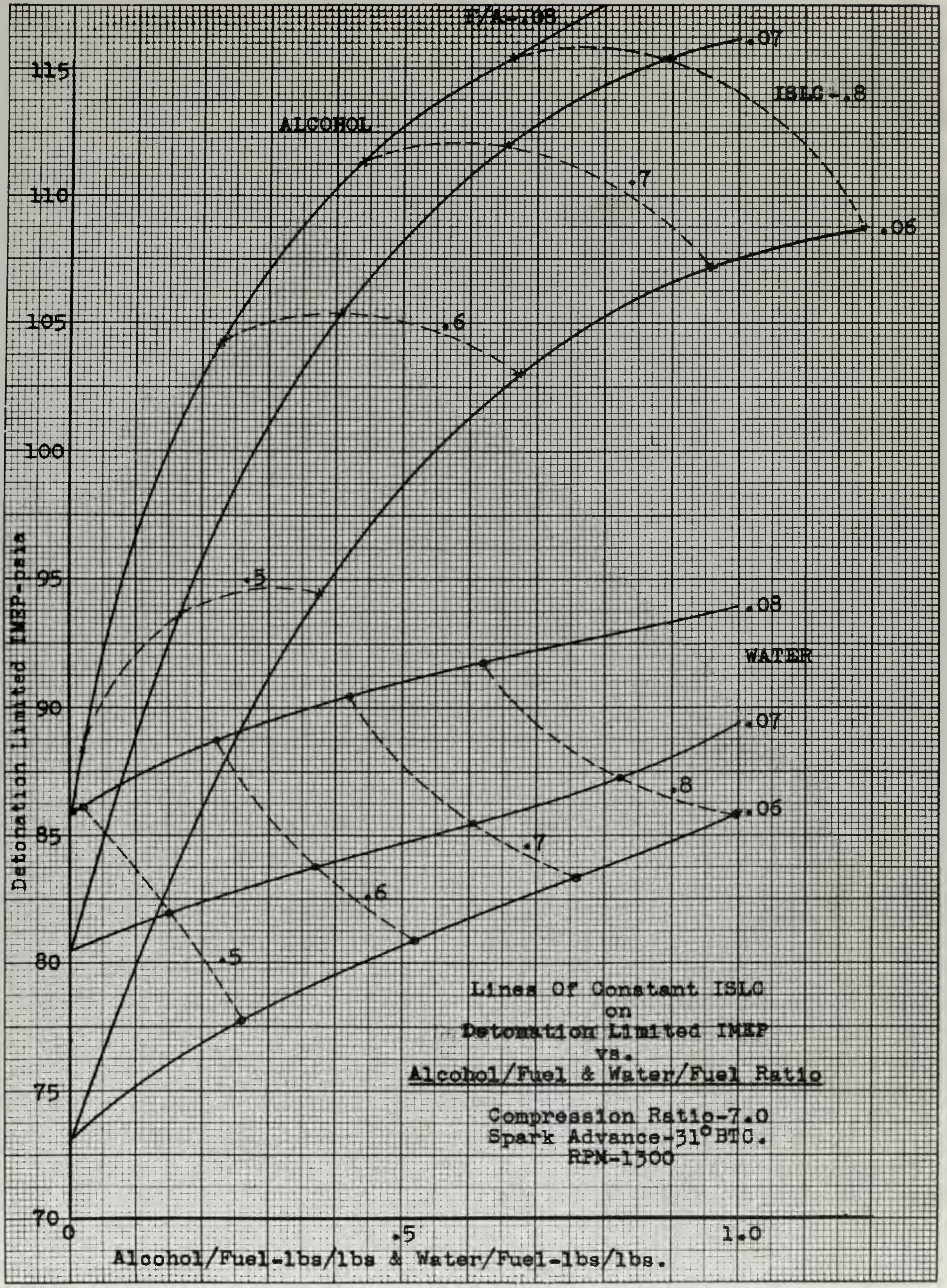
85
Detonation Limited IMEP-psia
0
.5
1.0
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs
ALCOHOL
F/A-.08
.07
.06
ISLC-.6
.5
.6
.5
.7
.8
.08
WATER
.07
.06
Lines Of Constant ISLC
on
Detonation Limited IMEP
vs.
Alcohol/Fuel & Water/Fuel Ratio
Compression Ratio-6.0
Spark Advance-31°BTC.
RPM-1300

Fig. 4


F/A-.08
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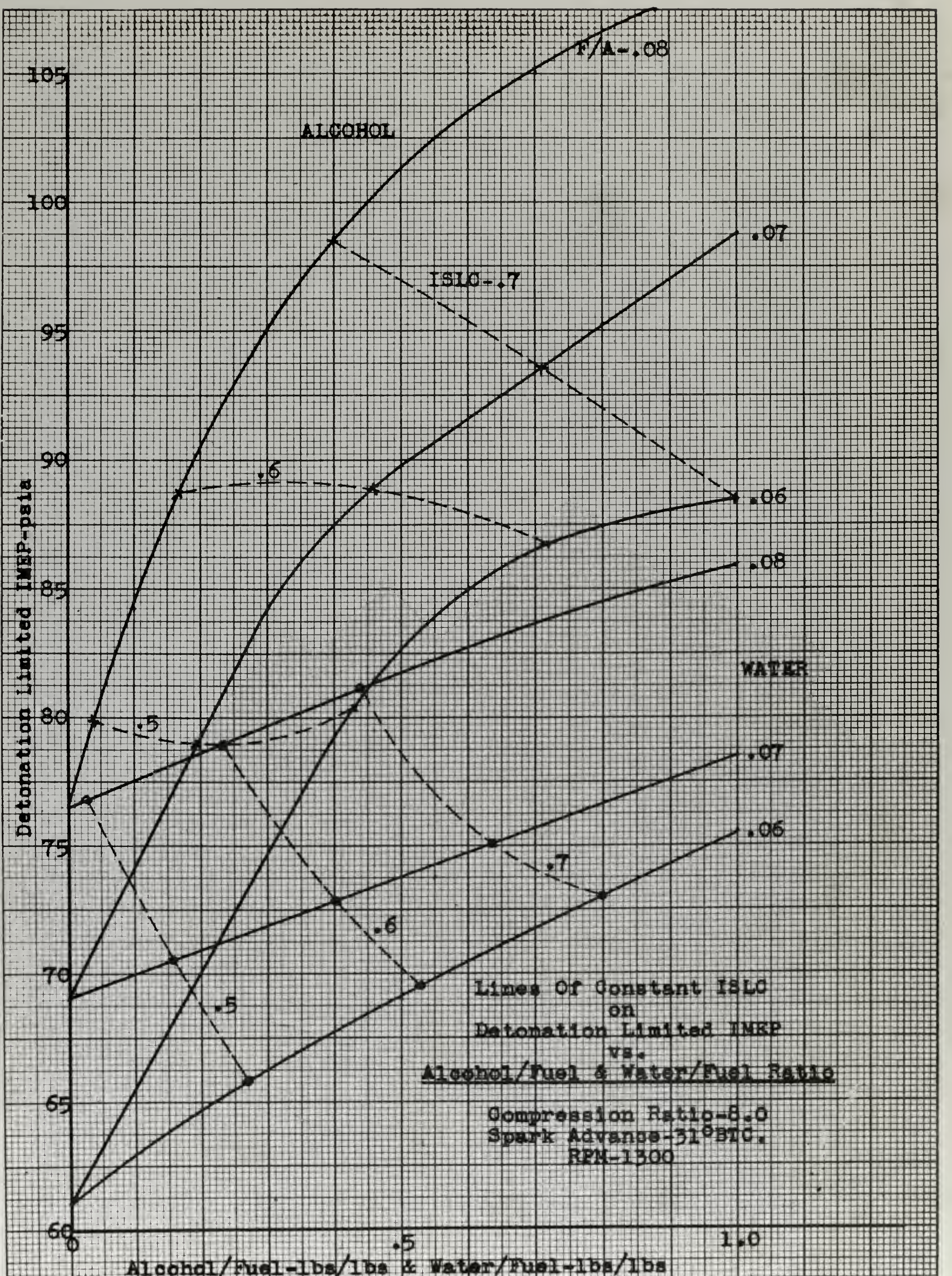
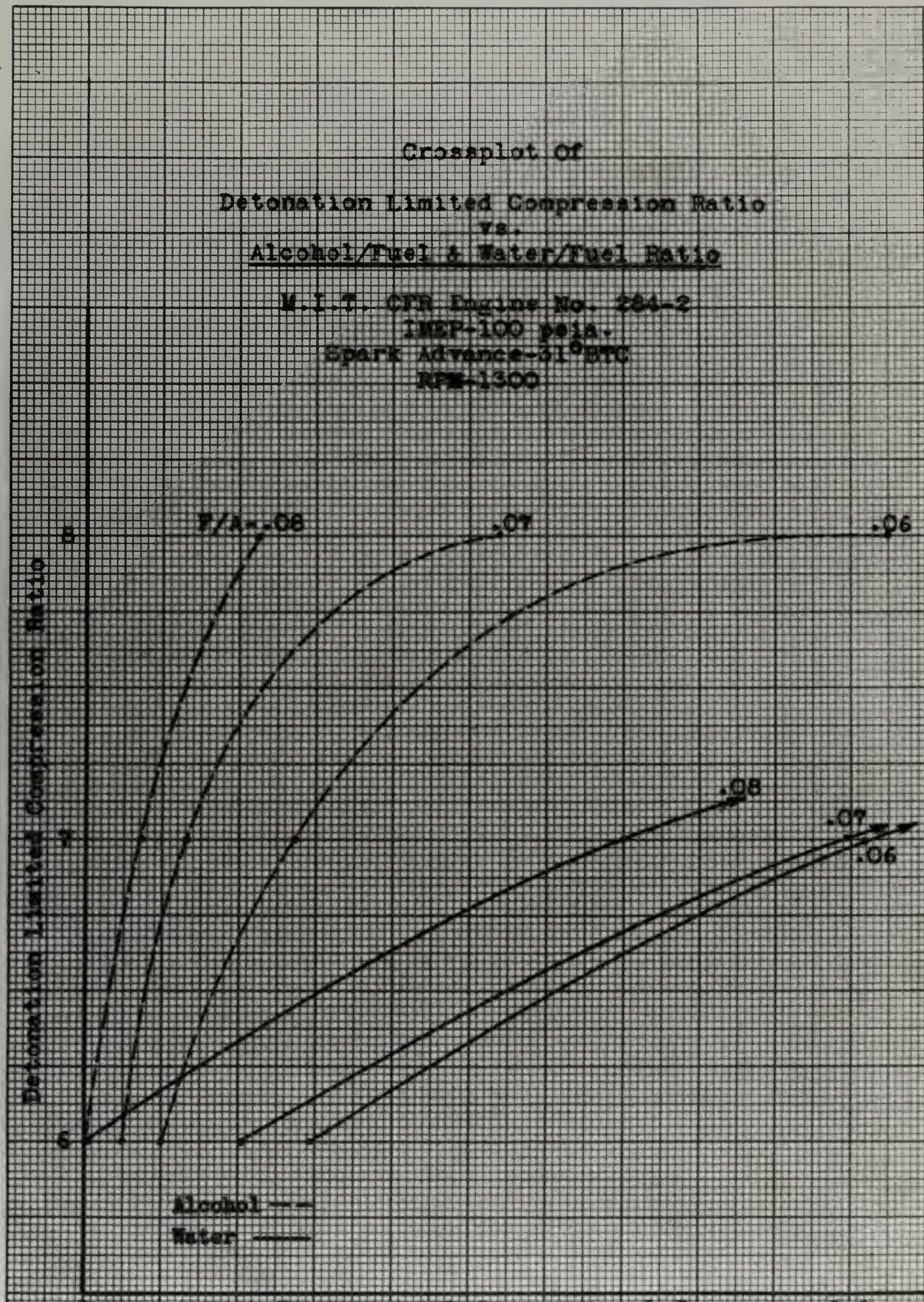
ISLC-.8
ALCOHOL
.7
.06
.6
.5
.08
WATER
.07
.8
.06
.7
.6
.5
115
110
105
100
95
90
85
80
75
70
0
.5
1.0
Detonation Limited IMEP-psia
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs.
Lines Of Constant ISLC
on
Detonation Limited IMEP
vs.
Alcohol/Fuel & Water/Fuel Ratio
Compression Ratio-7.0
Spark Advance-31° BTC.
RPM-1300

Fig. 5



F/A-.08
ALCOHOL
ISLC-.7
.07
.6
.06
.08
WATER
.5
.07
.06
.7
.6
.5
Lines Of Constant ISLC
on
Detonation Limited IMEP
vs.
Alcohol/Fuel & Water/Fuel Ratio
Compression Ratio-8.0
Spark Advance-31°BTC.
RPM-1300
105
100
95
90
85
80
75
70
65
60
Detonation Limited IMEP-psia
0
.5
1.0
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs

Fig. 6



Crossplot of
Detonation Limited Compression Ratio
vs.
Alcohol/Fuel & Water/Fuel Ratio
M.I.T. CFR Engine No. 284-2
IMEP-100 psia.
Spark Advance-31°BTC
RPM-1300
F/A-.08
.07
.06
.08
.07
.06
8
7
6
Alcohol
Water
0
.5
1.0
1.5
2.0
Detonation Limited Compression Ratio
Alcohol/Fuel-lbs/lbs & Water/Fuel-lbs/lbs.

Fig. 7

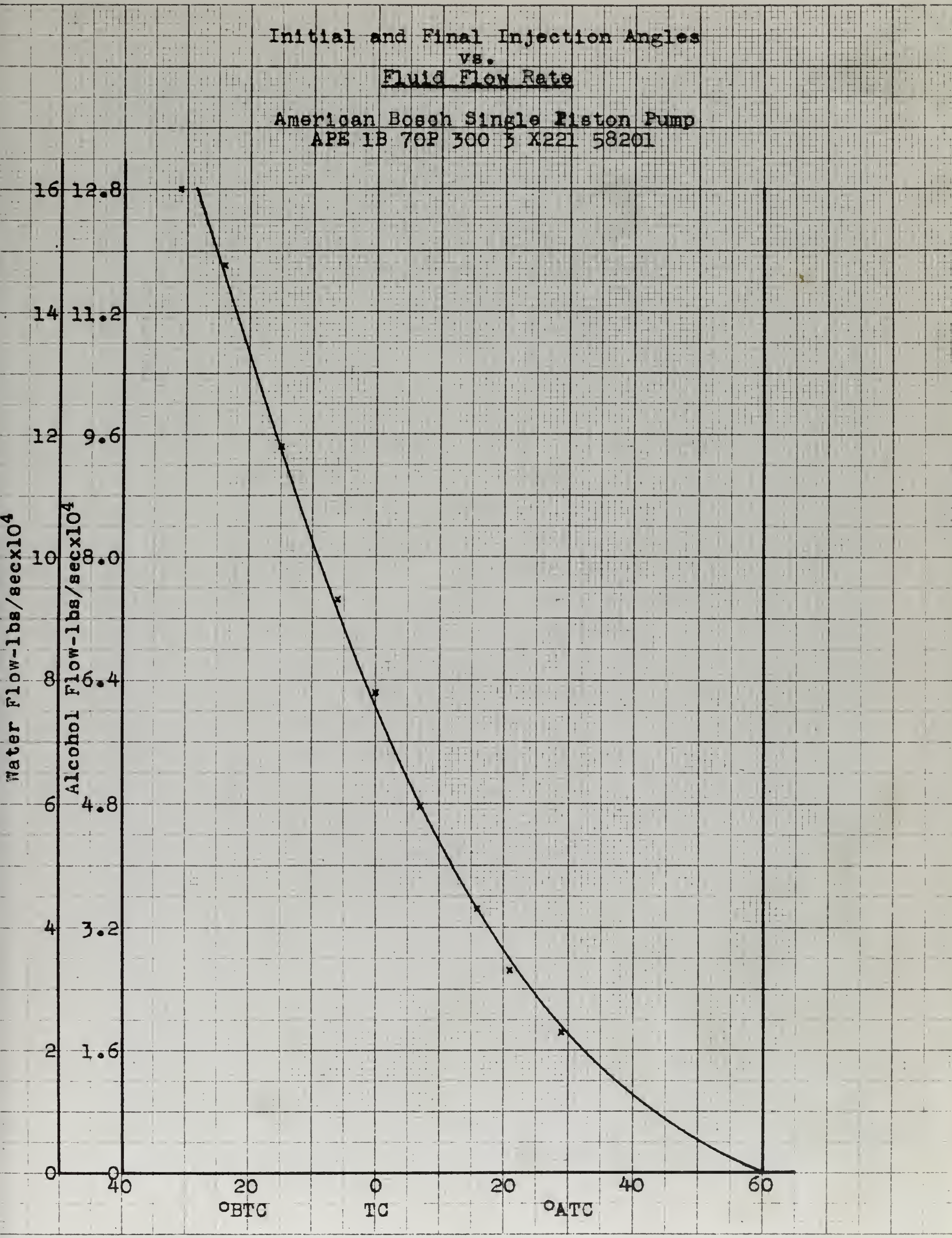
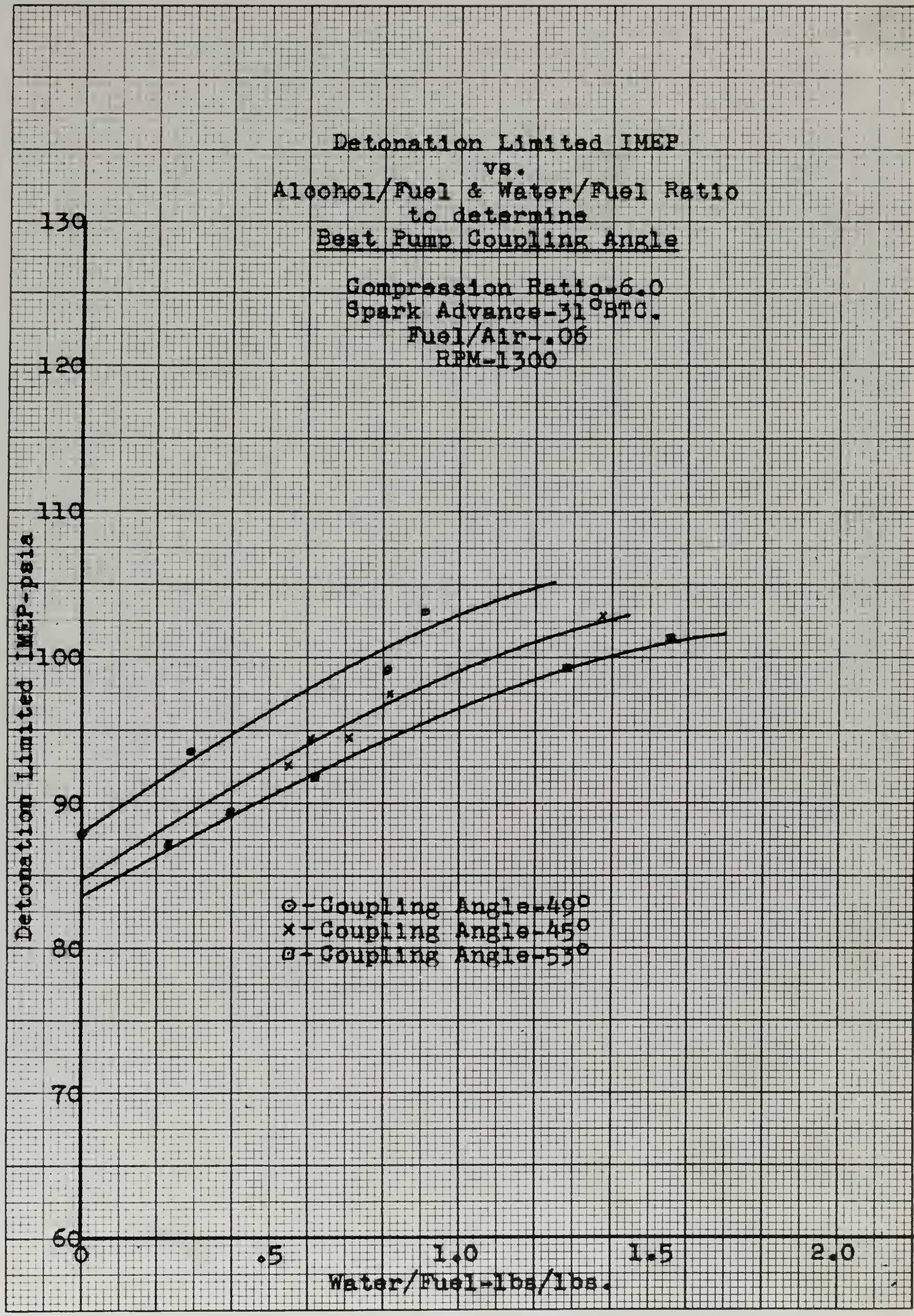
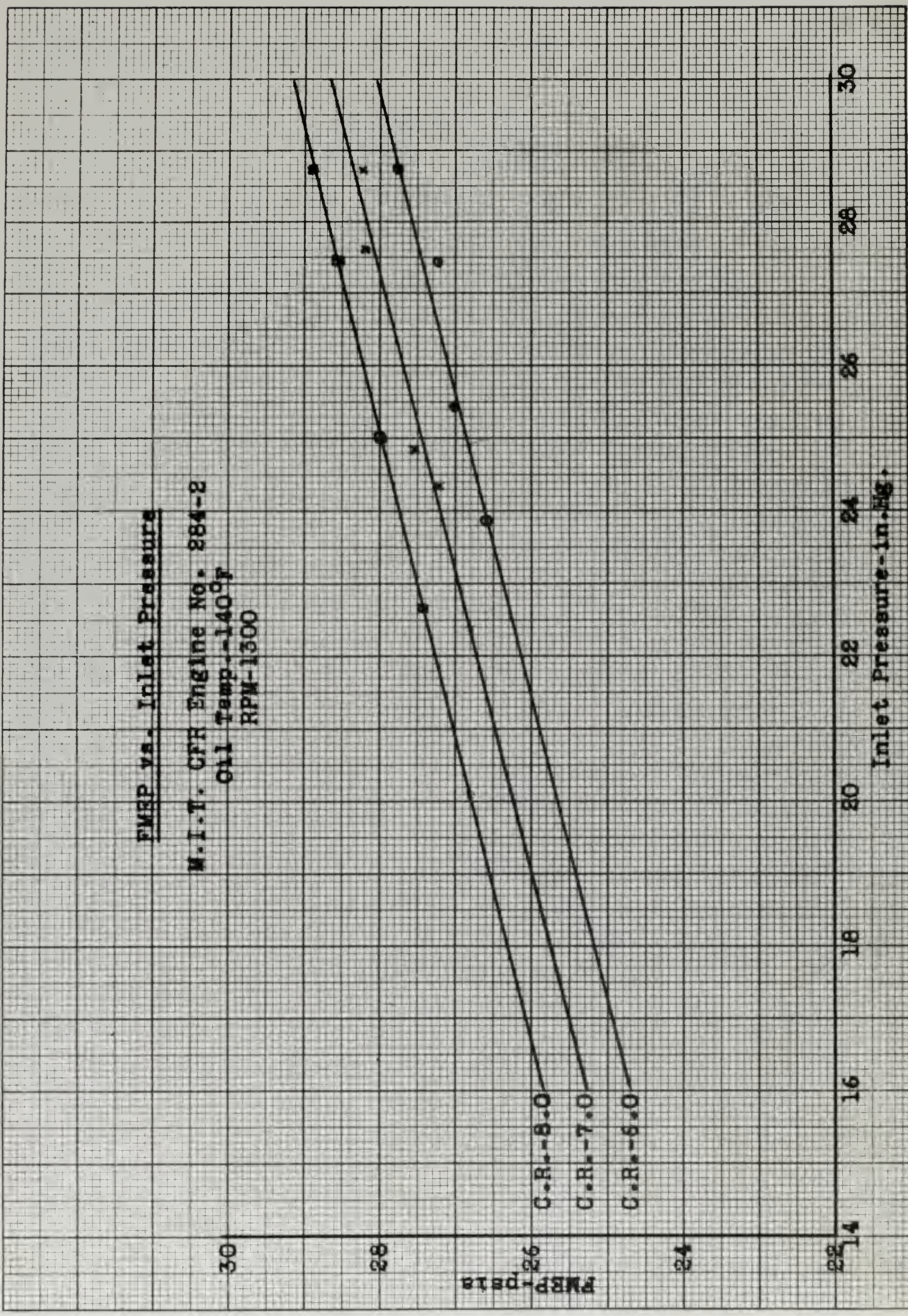

Initial and Final Injection Angles
vs.
Fluid Flow Rate
American Bosch Single Piston Pump
APE 1B 70P 300 3 X221 58201
Water Flow-lbs/secx10^4
Alcohol Flow-lbs/secx10^4
16 12.8
14 11.2
12 9.6
10 8.0
8 6.4
6 4.8
4 3.2
2 1.6
0 0
40
20
0
20
40
60
°BTC
TC
°ATC

Fig. 9



Detonation Limited IMEP
vs.
Alcohol/Fuel & Water/Fuel Ratio
to determine
Best Pump Coupling Angle
Compression Ratio-6.0
Spark Advance-31°BTC.
Fuel/Air-.06
RPM-1300
o - Coupling Angle-49°
x - Coupling Angle-45°
▫ - Coupling Angle-53°
Detonation Limited IMEP-psia
130
120
110
100
90
80
70
60
0
.5
1.0
1.5
2.0
Water/Fuel-lbs/lbs.

Fig. 10



FMEP vs. Inlet Pressure
M.I.T. CFR Engine No. 284-2
Oil Temp.-140°F
RPM-1300
C.R.-8.0
C.R.-7.0
C.R.-6.0
FMEP-psia
30
28
26
24
22
14
16
18
20
22
24
26
28
30
Inlet Pressure-in.Hg.

Fig. 11

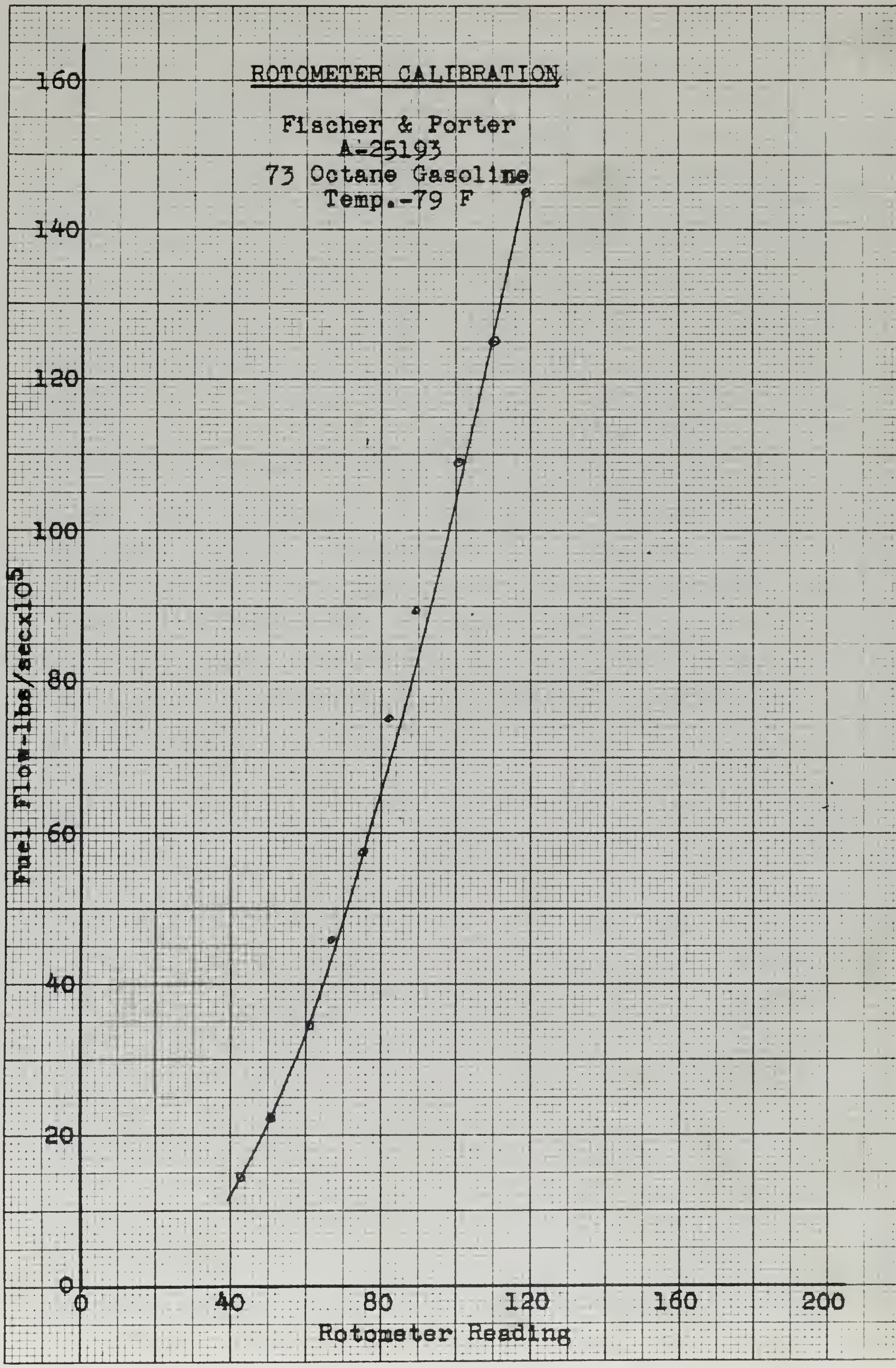

ROTOMETER CALIBRATION
Fischer & Porter
A-25193
73 Octane Gasoline
Temp.-79 F
Fuel Flow-lbs/secx10^5
0
20
40
60
80
100
120
140
160
0
40
80
120
160
200
Rotometer Reading

Fig. 12

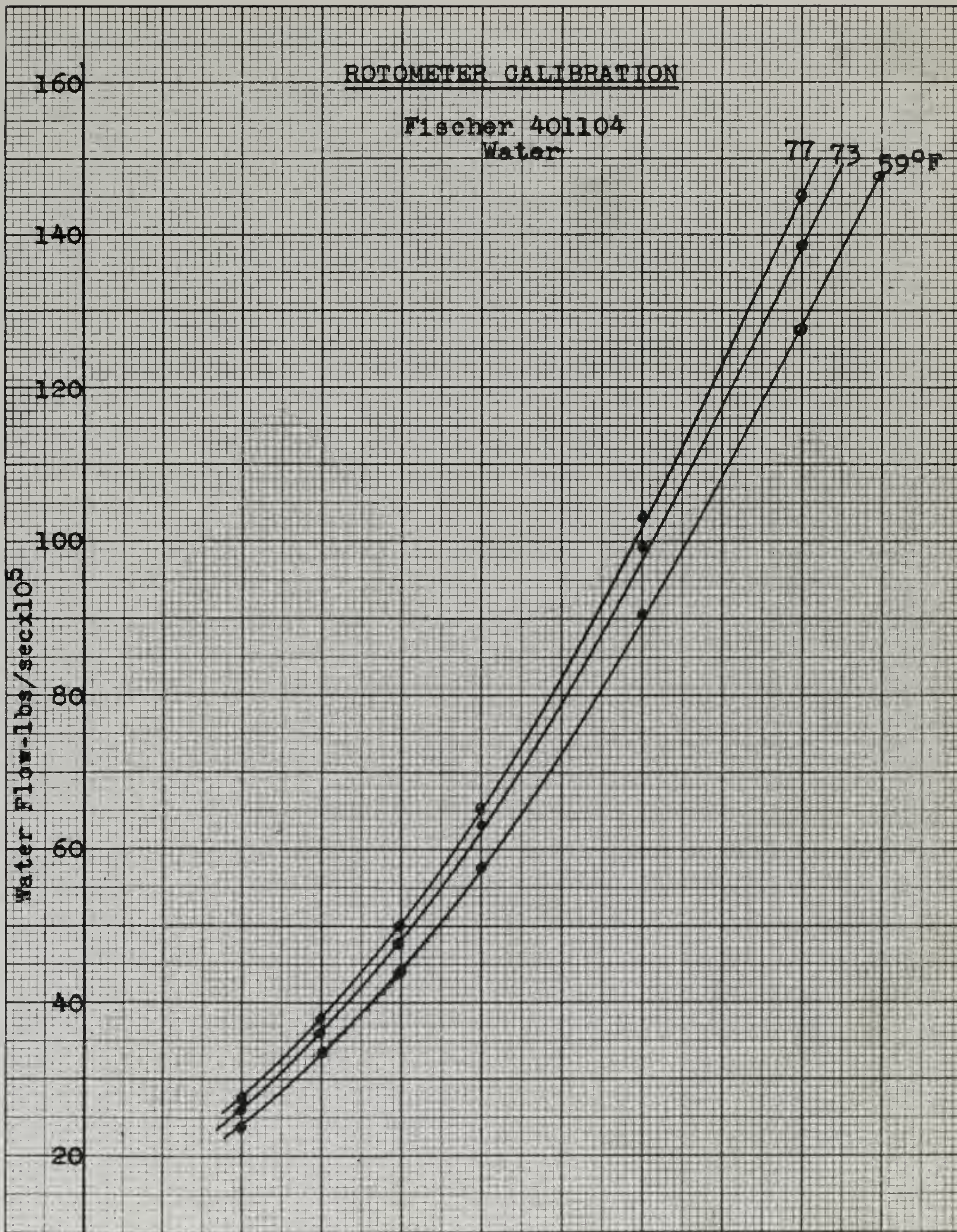

ROTOMETER CALIBRATION
Fischer 401104
Water
77
73
59°F
Water Flow-lbs/secx10^5
Rotometer Reading
0
20
40
60
80
100
120
140
160
0
40
80
120
160
200

Fig. 13

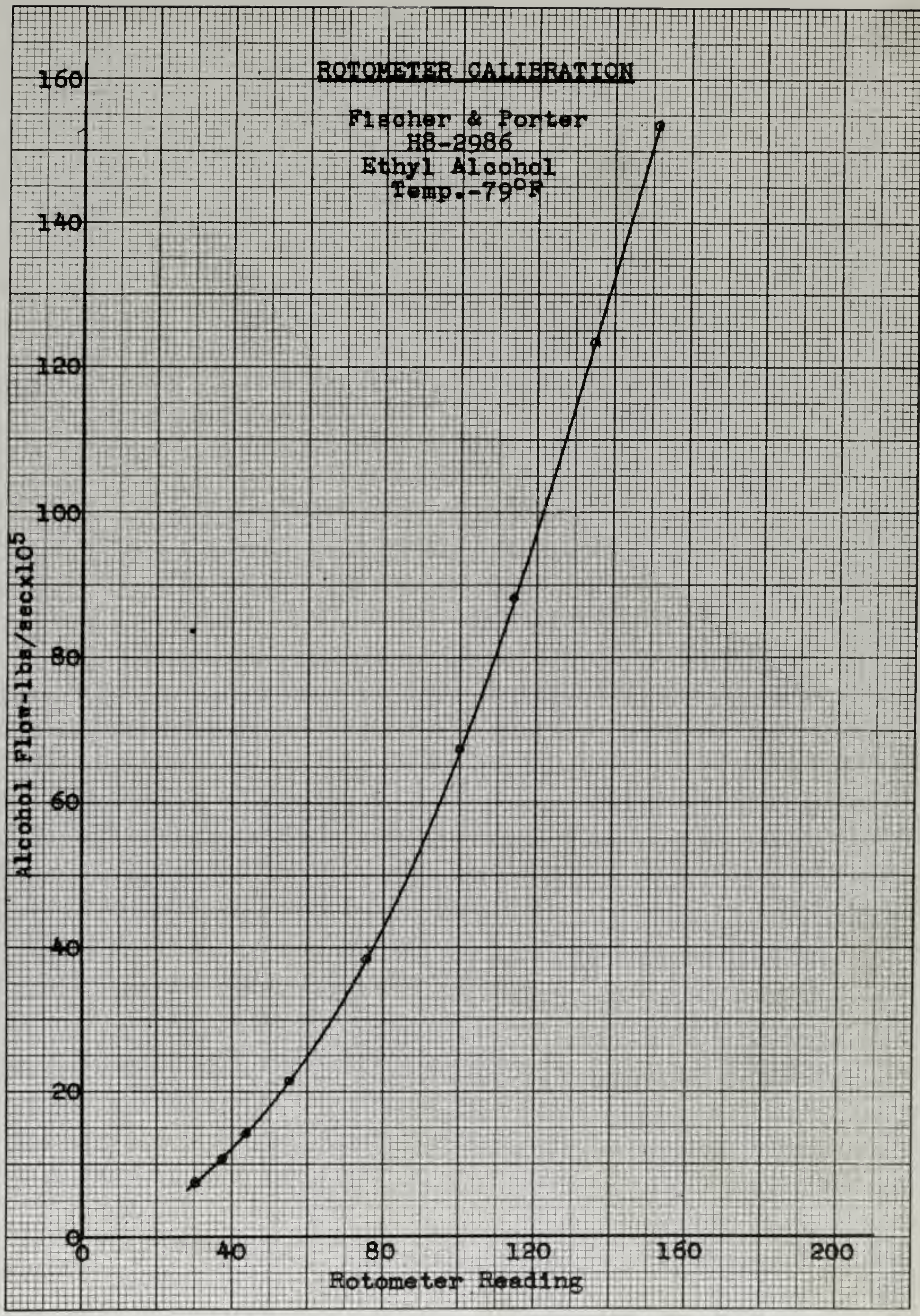

ROTOMETER CALIBRATION
Fischer & Porter
H8-2986
Ethyl Alcohol
Temp.-79°F
Alcohol Flow-lbs/secx10^5
Rotometer Reading
0
20
40
60
80
100
120
140
160
0
40
80
120
160
200

Fig. 14

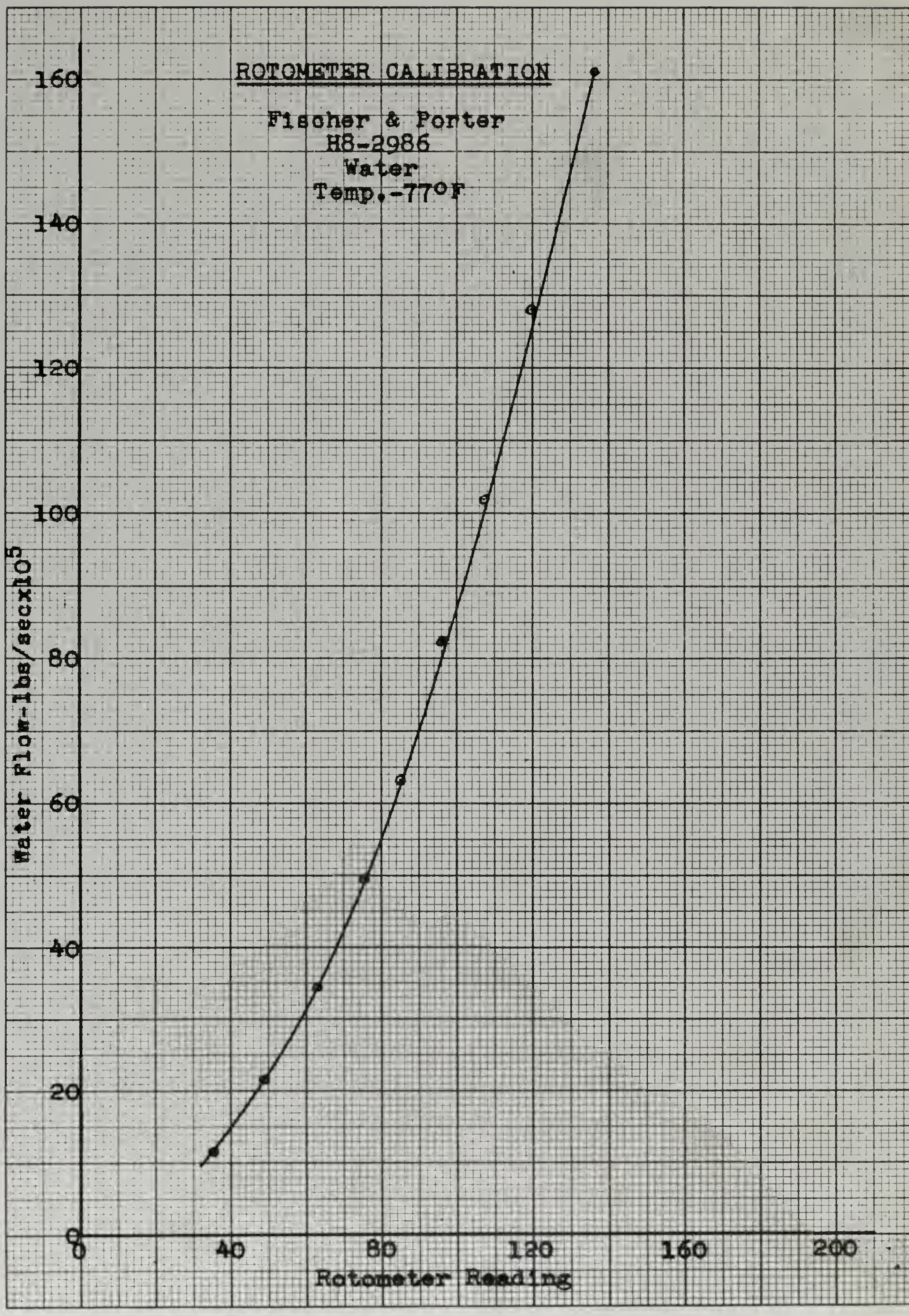

ROTOMETER CALIBRATION
Fischer & Porter
H8-2986
Water
Temp.-77°F
Water Flow-lbs/secx10^5
160
140
120
100
80
60
40
20
0
0
40
80
120
160
200
Rotometer Reading

Fig. 15

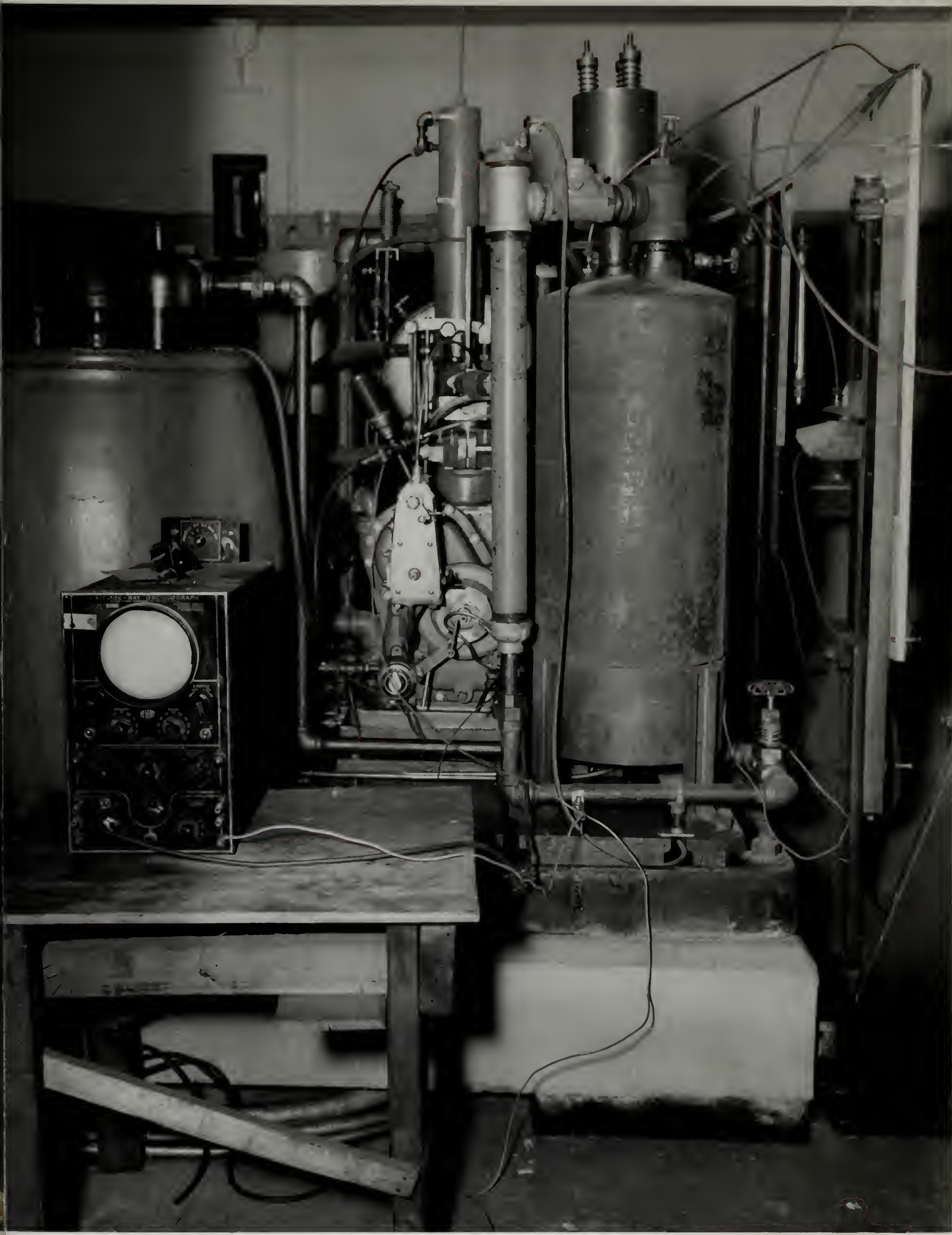


Fig. 15

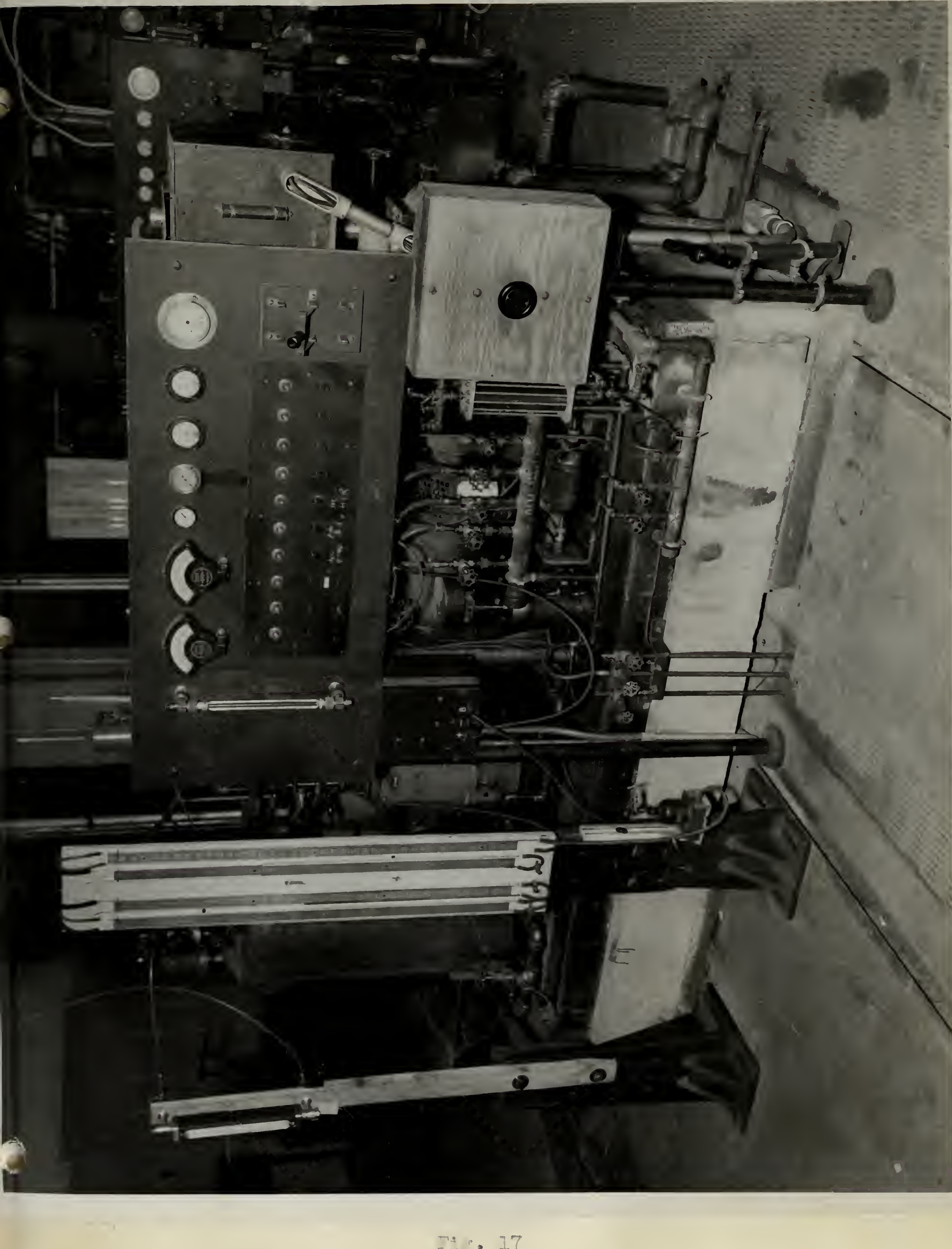


Fig. 17

Fig. 18

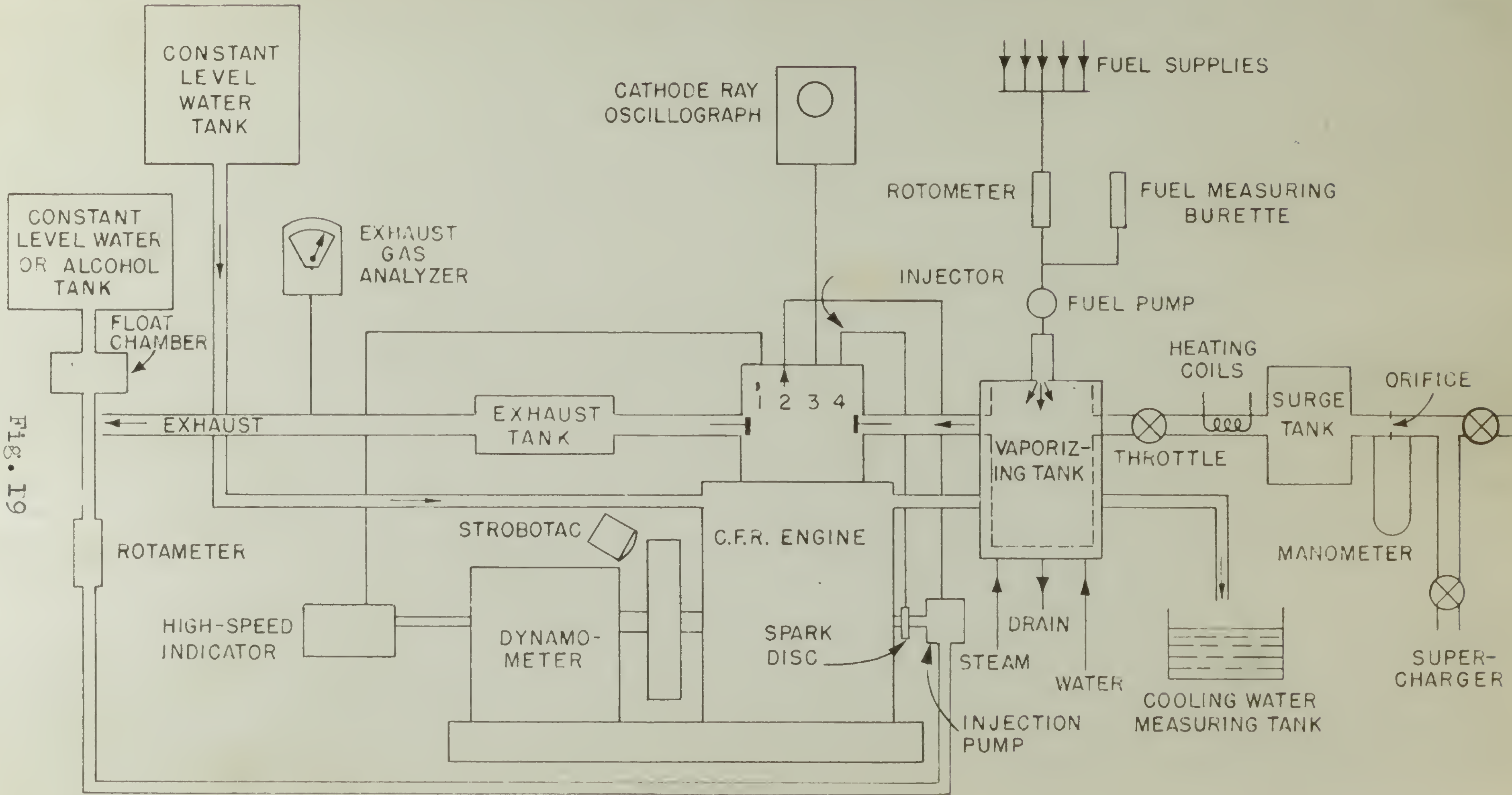
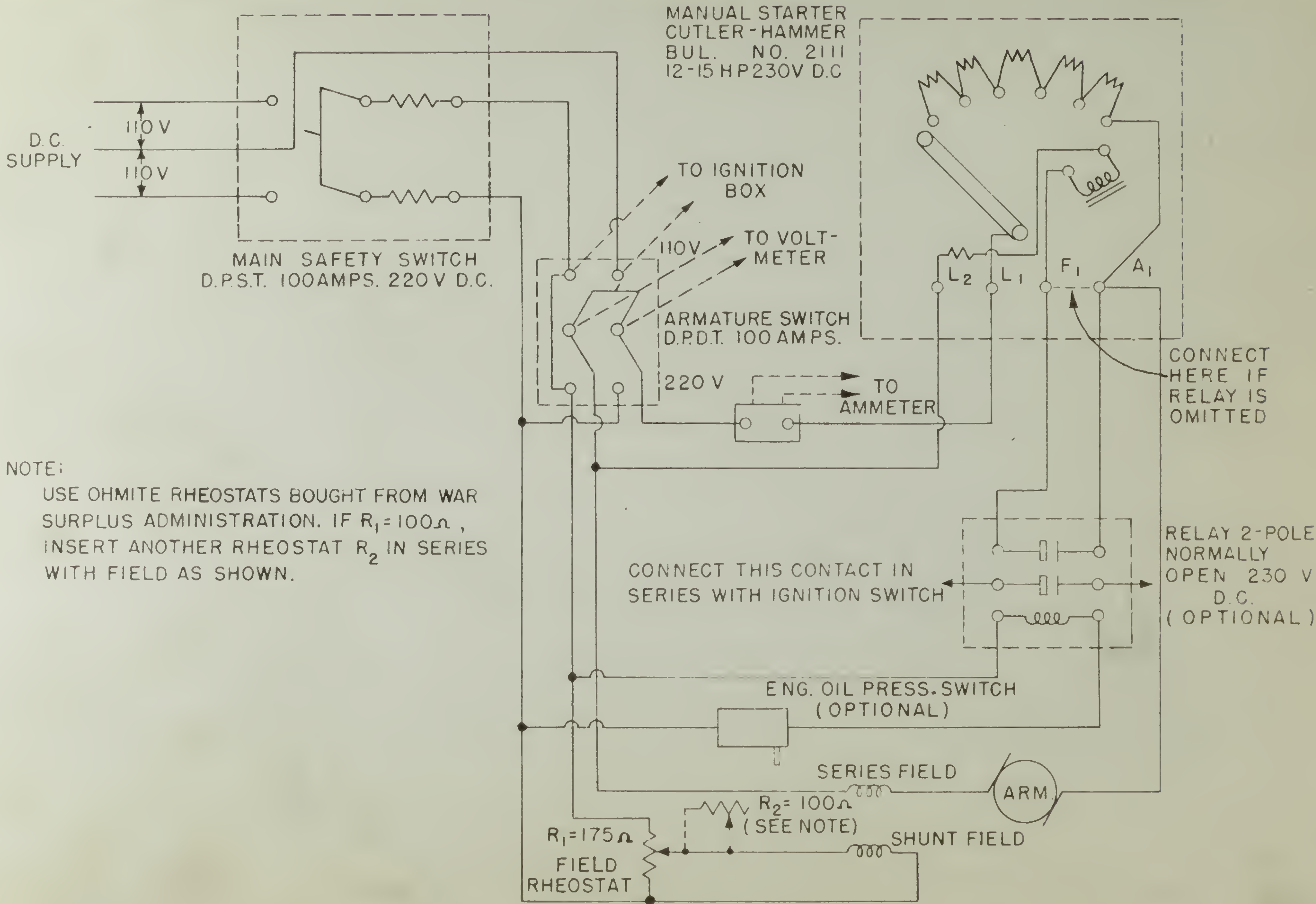


Fig. 19

1. INDICATOR PICKUP
2. WATER OR ALCOHOL INJECTION NOZZLE
3. RATE OF PRESSURE PICKUP
4. SPARK PLUG

C.F.R. ENGINE SETUP

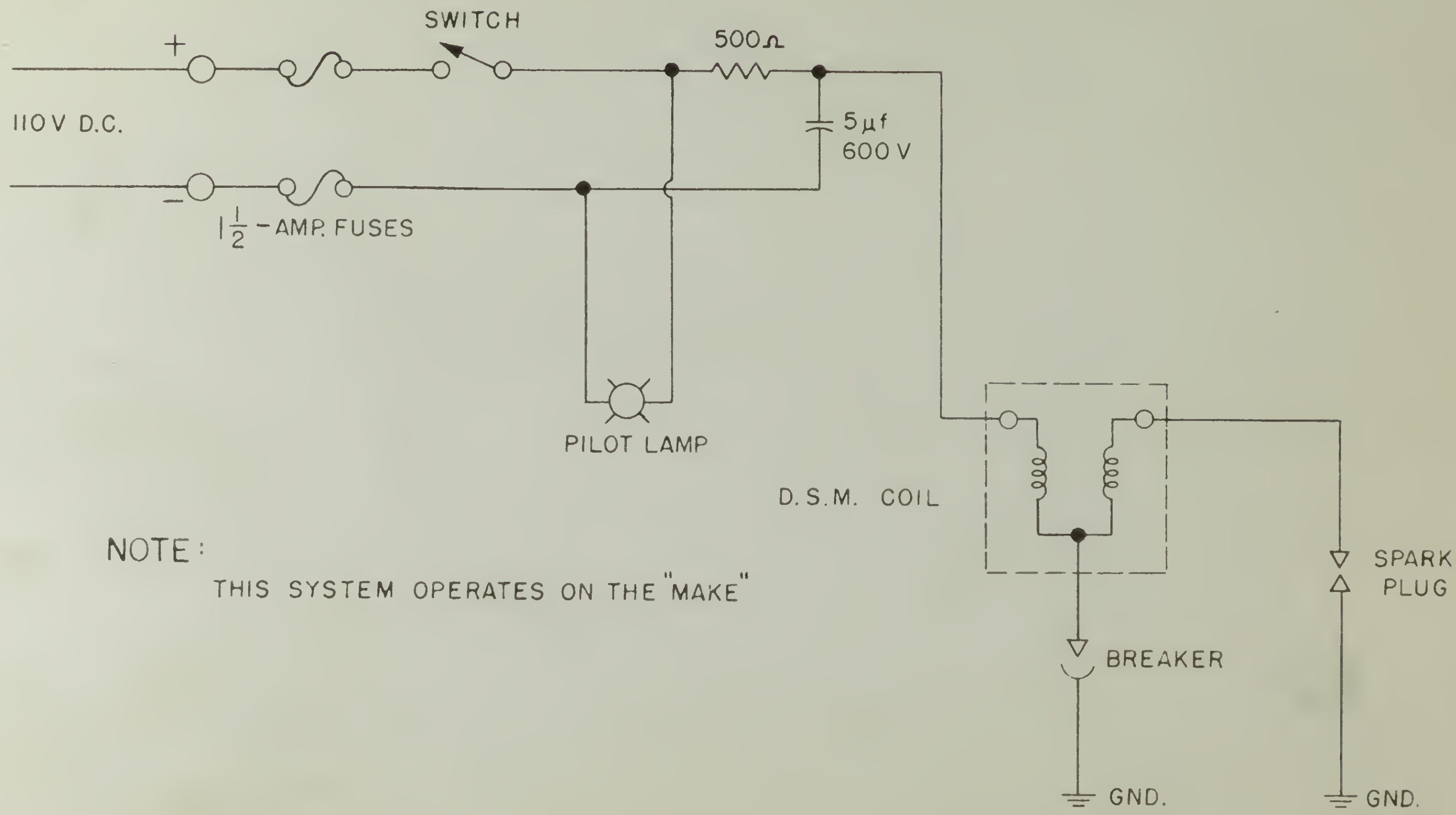


NOTE:

USE OHMITE RHEOSTATS BOUGHT FROM WAR SURPLUS ADMINISTRATION. IF $R_1 = 100\Omega$, INSERT ANOTHER RHEOSTAT R_2 IN SERIES WITH FIELD AS SHOWN.

WIRING DIAGRAM OF STAR DYNAMOMETER — CFR ENGINE SETUP

Fig. 20

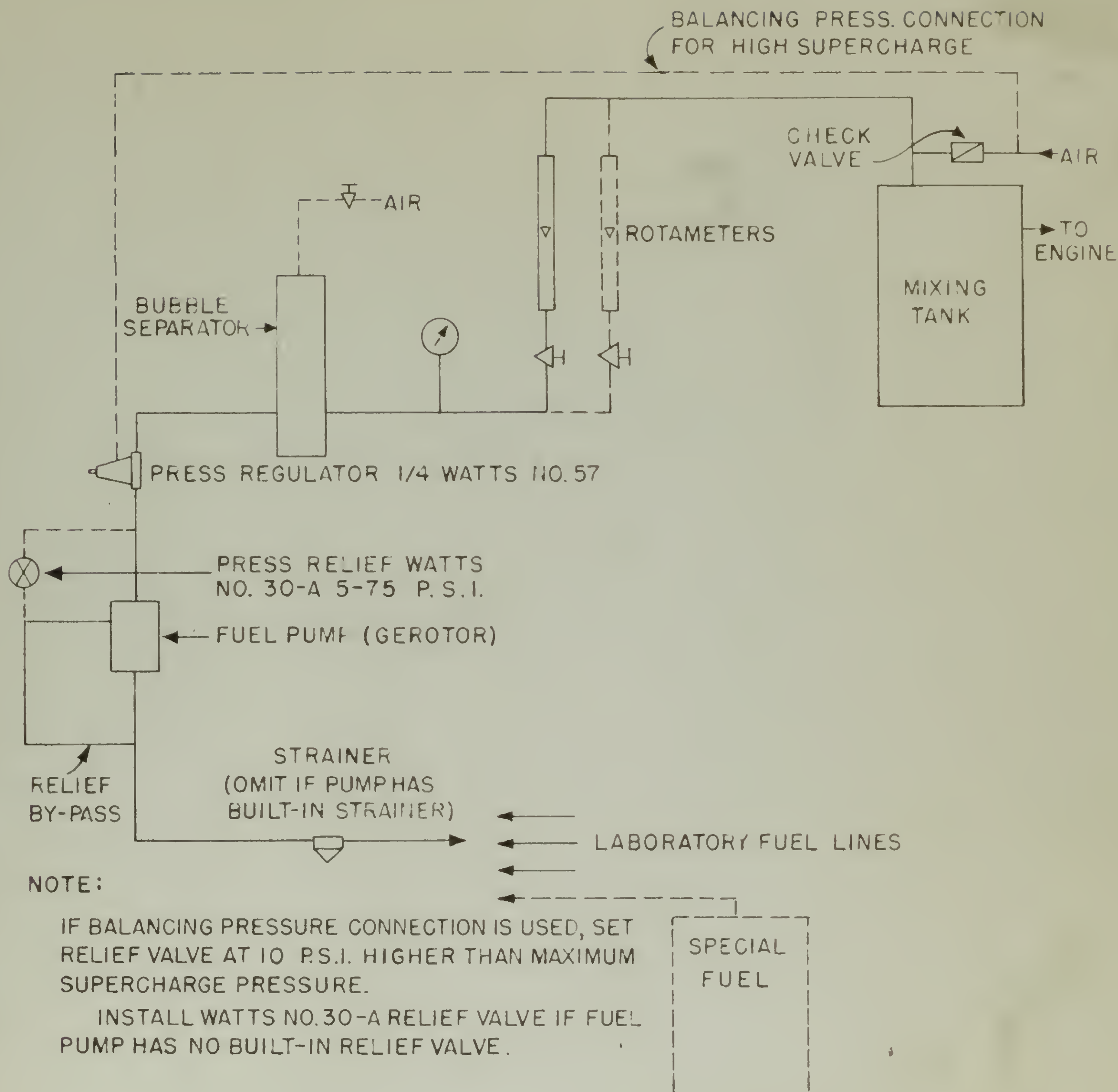


NOTE:

THIS SYSTEM OPERATES ON THE "MAKE"

WIRING DIAGRAM OF IGNITION SYSTEM

Fig. 21



SCHEMATIC DIAGRAM OF FUEL SYSTEM

Fig. 22

XI - EXPERIMENTAL DATA

Initial Angle of Injection vs. Mass Rate of Water Flow

Constant pump coupling angle - 49°
Constant RPM - 1300
Water temperature - 78°F

Roto. Rdg.	Angle	$lbs/sec \times 10^4$
200	31 BTC	16.0
183	24 BTC	14.75
154	15 BTC	11.8
130.5	6 BTC	9.3
114.5	0 TC	7.8
93	7 ATC	5.95
69	16 ATC	4.3
51.5	21 ATC	3.3
36	29 ATC	2.3

ROTOMETER CALIBRATION

Fischer & Porter
H8-2986

Alcohol
Temperature 79°F

Roto. Rdg.	W gms	T sec	lbs/secx10^5
30	4	114.9	7.67
37.5	5	103.3	10.68
44	3	46.7	14.14
55.5	10	102.9	21.4
76	10	57.26	38.4
100	20	65.3	67.5
114	20	49.9	88.4
135	30	53.6	123.2
151	30	43.1	153.5
165	40	49.8	177.0
197	40	36.6	241.0

Water
Temperature 77°F

Roto. Rdg.	W gms	T sec	lbs/secx10^5
35.5	10	185.1	11.92
49	5	51.9	21.25
63	10	64.2	34.3
75	10	44.6	49.5
85	15	52.4	63.0
96	20	53.3	82.8
107	25	54.1	102.0
120	20	34.3	128.7
135.5	40	54.8	161.0
150.5	30	33.7	196.3

ROTOMETER CALIBRATION

Fischer & Porter
A-25193

Gasoline 73 Octane
Temperature 78°F

Roto. Rdg.	W gms	T sec	lbs/sec$\times10^3$
43	10	152.5	.145
50.5	10	99.3	.222
61.0	10	63.7	.346
67	30	144.5	.458
75	10	38.4	.575
82	30	88.3	.75
89.5	20	49.6	.889
101	20	40.5	1.09
111	30	53.0	1.25
119	40	61.9	1.425
128	20	28.5	1.55
135	50	64.7	1.70
145	50	59.6	1.85
176	50	37.2	2.96
198	50	30.6	3.60

EXPERIMENT NO. ____ TITLE *Determination of Best Pump Coupling Angle* DATE *4/3/47* SLOAN LABORATORY

ENGINE ____ FUEL *73 Octane* S.G. *.719* WET BULB ____ DRY BULB *77°F*

BORE *3.25"* STROKE *4.50"* COMPRESSION RATIO *6.0* BAROMETER (ACT.) *769.6 mm Hg* (CORR.) *30.196 "Hg*

CONSTANTS BMEP = B.L. X *4.245* BHP = B.L. x RPM

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto	Water Roto	Water Cons.	Orifice Δp	Pi Δp	$\frac{W_w}{W_f}$	Angle of Coupling	Angle of Injection	Bmep	Fmep	Imep	Liquid Cons	IHP	Isfc
						°F	°F	psi	"Hg	"H_2O	°F	lbs/sec	lbs/sec		°BTC			x 10³ lbs/sec	"H_2O	"Hg			°BTC °ATC	psia	psia	psia	x 10³ lbs/sec		lbs Liq./IHP-hr
Coupling Angle = 49° 4/29/47																													
These Runs Served	1430	1	1300	17.8		142	211	66	29.07	15.6	137	.01238	.000743	.06	31	83	87	.673	8.20	1.07	.906	49	9.2°A	75.5	27.7	103.2	1.416	6.32	.806
as Check Runs for	1440	2	1300	17.0		142	211	66	26.50	15.4	137	.01148	.000689	.06	31	80	68	.400	7.05	3.64	.581	49	16°A	72.1	27.1	99.2	1.089	6.07	.645
C.R. = 6.0 F = .06	1450	3	1300	15.7		140	211	66	25.70	15.2	140	.01052	.000632	.06	31	77	46	.188	5.95	4.44	.297	49	24°A	66.6	26.9	93.5	.820	5.72	.516
Water Injection	1500	4	1300	14.5		144	212	66	23.67	15.1	140	.00985	.000592	.06	31	75	0	0	5.20	6.47	0	49	—	61.5	26.5	88.0	.592	5.39	.396
Coupling Angle = 53°	1350	1	1300	17.4		140	210	65	27.76	16.8	140	.01222	.000733	.06	31	82.5	151	1.147	8.00	2.44	1.562	53	5.5°B	73.9	27.5	101.4			
(Injection Retarded 8°)	1410	2	1300	17.0		140	210	65	26.30	16.8	140	.01150	.000690	.06	31	80	130.5	.882	7.09	3.90	1.280	53	1.7°A	72.2	27.2	99.4			
	1420	3	1300	14.8		140	210	65	23.86	16.4	140	.01020	.000612	.06	31	76	39	.242	5.59	6.34	.395	53	34.5°A	62.8	26.6	89.4			
	1445	4	1300	15.3		140	210	65	24.69	16.5	140	.01068	.000641	.06	31	77.5	64	.397	6.10	5.51	.620	53	25.5°A	65.0	26.8	91.8			
	1500	5	1300	14.3		140	210	65	23.35	16.4	140	.01020	.000612	.06	31	76	12	.143	5.60	6.85	.233	53	44.5°A	60.7	26.5	87.2			
Coupling Angle = 45°	1530	1	1300	17.8		140	210	65	27.60	16.8	140	.012130	.000728	.06	31	82	138	1.005	7.88	2.60	1.380	45	17°B	75.5	27.5	103.0			
(Injection Advanced 8°)	1545	2	1300	15.5		140	210	65	25.05	16.5	140	.01083	.000650	.06	31	78	57	.358	6.50	5.15	.551	45	12°A	65.8	26.8	92.6			
	1600	3	1300	15.9		140	210	65	25.52	16.6	140	.01117	.000670	.06	31	79	77.5	.475	6.70	4.68	.709	45	4.5°A	67.5	27.0	94.5			
	1610	4	1300	15.9		140	210	65	25.52	16.6	140	.01117	.000670	.06	31	79	66	.407	6.70	4.68	.607	45	8.7°A	67.5	27.0	94.5			
	1620	5	1300	16.6		140	210	65	26.15	16.7	140	.01147	.000688	.06	31	80	89.5	.563	7.05	4.05	.819	45	0.2°A	70.5	27.1	97.6			

COURSE
GROUP
NAMES

EXPERIMENT NO. ____ TITLE *Alcohol Injection* DATE *4/16/47* SLOAN LABORATORY

ENGINE *CFR-9B* FUEL *73 Octane* S.G. *.719* WET BULB *—* DRY BULB *76°F*

BORE *3.25*" STROKE *4.50*" COMPRESSION RATIO *6.0* BAROMETER (ACT.) *767.4 mm Hg.* (CORR.) *30.103 "Hg*

CONSTANTS BMEP = B.L. X BHP = $\frac{\text{B.L. x RPM}}{}$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_I	P_E	T_I	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto.	Alc. Roto.	Alc. Cons.	W_{alc}/W_f	Orifice ΔP	P_i ΔP	BMEP	FMEP	IMEP	Liq. Cons.	IHP	isfc
				"Hg		°F	°F	psi	"Hg.	"H_2O	°F	lbs/sec.	lbs./sec		°BTC			lbs/sec x 10^{-3}		"H_2O	"Hg	psia	psia	psia	lbs/sec x 10^{-3}		lbs/IHP-hr
	1145	1	1300	14.7		142	211	67	23.0	15.0	140	.01003	.000601	.06	31	75.5	0	0	0	5.35	7.09	62.4	26.4	88.8	.601	5.44	.399
	1155	2	"	17.1		138	212	67	24.9	15.1	140	.01085	.000650	"	"	78	43	.135	.208	6.25	5.20	72.5	26.8	99.3	.785	6.09	.464
	1205	3	"	18.4		139	212	66	25.85	15.3	141	.01134	.000680	"	"	79.5	57	.224	.330	6.81	4.25	78.0	27.0	105.0	.904	6.44	.505
	1215	4	"	20.3		140	210	66	27.50	15.5	140	.01215	.000728	"	"	82	73	.354	.486	7.84	2.60	86.0	27.5	113.5	1.082	6.95	.562
	1225	5	"	21.9		140	210	66	28.92	15.7	140	.01282	.000767	"	"	84	99	.660	.861	8.74	1.18	92.9	27.7	120.6	1.427	7.40	.694
	1355	1	"	15.2		141	208	66	23.10	15.2	140	.00990	.000693	.07	"	80	0	0	0	5.24	7.0	64.5	26.4	90.9	.693	5.56	.449
	1405	2	"	16.5		142	207	66	24.16	15.2	140	.01038	.000728	"	"	82	23	.055	.0756	5.79	6.94	70.0	26.6	96.6	.783	5.92	.476
	1415	3	"	17.7		142	210	67	25.19	15.3	140	.01094	.000767	"	"	84	40	.119	.155	6.39	4.91	75.0	26.9	101.9	.886	6.24	.512
	1420	4	"	18.9		142	211	66	27.19	15.4	140	.01150	.000806	"	"	86	54	.203	.252	7.09	2.91	80.1	27.3	107.4	1.009	6.59	.551
	1425	5	"	20.2		143	211	66	27.43	15.4	140	.01203	.000844	"	"	88	69	.317	.376	7.76	2.67	85.6	27.4	113.0	1.161	6.92	.605
	1430	6	"	21.8		143	211	66	28.96	15.7	140	.01280	.000899	"	"	91	77	.395	.440	8.74	1.14	92.5	27.7	120.2	1.294	7.36	.634
	1500	1	"	21.5		144	211	66	28.87	15.7	145	.01272	.001018	.08	"	97	63	.267	.262	8.66	1.14	91.3	27.7	119.0	1.285	7.30	.634
	1510	2	"	20.4		143	211	66	27.81	15.6	140	.01222	.000977	"	"	95	56	.218	.223	7.95	2.20	86.5	27.4	113.9	1.195	6.97	.618
	1515	3	"	19.4		142	211	66	27.02	15.6	141	.01177	.000940	"	"	93	43	.135	.144	7.49	2.99	82.3	27.2	109.5	1.075	6.71	.576
	1520	4	"	18.4		141	211	66	25.96	15.4	142	.01128	.000902	"	"	91	26	.063	.069	6.81	4.05	78.0	27.0	105.0	.965	6.44	.540
	1530	5	"	17.4		144	211	66	25.17	15.3	141	.01088	.000870	"	"	89.5	0	0	0	6.34	4.84	73.9	26.8	100.7	.870	6.16	.508

COURSE
GROUP
NAMES

EXPERIMENT NO. ______ TITLE *Water Injection* DATE *3/27/47* SLOAN LABORATORY

ENGINE *CFR 9-B* FUEL *73 Octane* S.G. *.719* WET BULB ______ DRY BULB *77°F*

BORE *3.25"* STROKE *4.50"* COMPRESSION RATIO *6.0* BAROMETER (ACT.) *760.2 mm Hg* (CORR.) *29.825 "Hg*

CONSTANTS BMEP = B.L. X *4.245* BHP = $\frac{\text{B.L.} \times \text{RPM}}{}$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto	Water Roto	Water Cons.	$\frac{W_w}{W_a}$	Orifice Δp	P_i Δp	Bmep	Fmep	Imep	Liquid Cons.	IHP	Islc
				"Hg		°F	°F	psi	"Hg	"H_2O	°F	lbs/sec	lbs./sec		°BTC			x10³ lbs/sec		"H_2O	"Hg	psia	psia	psia	x10³ lbs/sec		lbs.Liq./IHP-hr
		1	1300	19.6		140	208	66	28.62	16.7	140	.01275	.000767	.06	31	84.0	145	1.084	1.414	8.79	1.22	83.1	27.6	110.7	1.851	6.78	.985
		2	1300	19.1		140	207	66	28.60	16.7	140	.01270	.000764	.06	31	83.5	128	.915	1.198	8.66	1.24	81.0	27.6	108.6	1.679	6.65	.908
		3	1300	18.8		140	208	66	27.79	16.6	140	.01245	.000747	.06	31	83.0	128	.905	1.210	8.35	2.05	79.7	27.4	107.1	1.652	6.56	.906
		4	1300	18.6		140	208	66	27.24	16.6	140	.012100	.000728	.06	31	82.0	104	.663	.911	7.91	2.60	78.9	27.3	106.2	1.391	6.50	.771
		5	1300	18.2		140	208	66	26.61	16.6	140	.01180	.000708	.06	31	81.0	91	.575	.812	7.52	3.23	77.1	27.2	104.3	1.283	6.39	.725
		6	1300	16.2		140	208	66	24.57	16.4	140	.01084	.000650	.06	31	78.0	27	.210	.323	6.34	5.27	68.7	26.7	95.4	.860	5.83	.532
		7	1300	17.6		140	208	66	26.22	16.6	140	.01150	.000690	.06	31	80.0	73	.447	.6475	7.25	3.62	74.6	27.1	101.7	1.137	6.22	.658
		8	1300	17.0		140	208	66	25.15	16.6	140	.01120	.000670	.06	31	79.0	49.5	.318	.474	6.74	4.69	72.1	26.8	98.9	.988	6.05	.588
		1	1300	20.2		140	208	66	28.80	16.8	140	.01275	.000885	.07	31	90.5	182	1.478	1.670	8.73	1.06	85.6	27.6	113.2	2.363	6.94	1.230
		2	1300	19.4		140	208	66	27.47	16.7	140	.01208	.000845	.07	31	88	156.5	1.203	1.424	7.82	2.40	82.2	27.3	109.5	2.048	6.71	1.100
*		3	1300	19.0		142	210	66	29.10	15.7	139	.01215	.000850	.07	31	88.5	100	.902	1.061	7.90	1.04	80.6	27.7	108.3	1.752	6.64	.951
		4	1300	18.9		142	210	66	26.29	16.5	138	.01150	.000805	.07	31	86	117.5	.805	1.000	7.06	3.58	80.1	27.1	107.1	1.610	6.41	.905
*		5	1300	18.3		140	211	66	27.79	15.4	140	.01150	.000805	.07	31	86	87	.674	.836	7.10	2.35	77.6	27.4	105.0	1.479	6.45	.825
F = .07 *		6	1300	17.2		137	211	66	26.05	15.3	138	.01068	.000747	.07	31	83	60	.311	.416	6.10	4.09	73.1	27.04	100.1	1.058	6.14	.620
*Runs made 4/29/47		7	1300	16.1		140	210	66	24.87	16.3	140	.01040	.000727	.07	31	82	6	.112	.154	5.78	5.00	68.2	26.8	95.0	.839	5.81	.521
Bar. 30.136"Hg																											
*		1	1300	20.6		140	208	66	29.17	16.9	139	.01210	.000979	.08	31	95	171.5	1.300	1.335	8.61	1.10	88.4	27.70	116.1	2.274	7.12	1.15
COURSE 4/29/47		2	1300	19.5		141	209	66	29.08	15.7	141	.01203	.000967	.08	31	94.5	99.5	.894	.924	7.75	1.06	82.8	27.7	110.5	1.861	6.76	.992
GROUP *		3	1300	18.6		140	209	66	27.04	16.8	141	.01172	.000939	.08	31	93.2	120	.760	.810	7.31	3.23	79.8	27.25	107.05	1.699	6.58	.930
NAMES 4/29/47		4	1300	18.5		143	211	66	27.77	15.4	140	.01150	.000925	.08	31	92	86	.656	.710	7.10	2.37	78.5	27.40	105.9	1.581	6.48	.88
*		5	1300	17.9		142	210	66	26.02	16.6	140	.01129	.000902	.08	31	91	82.5	.495	.549	6.76	4.25	76.8	27.0	103.8	1.397	6.35	.792
4/29/47		6	1300	18.1		142	203	66	27.23	15.9	141	.01124	.000902	.08	31	91	77	.517	.573	6.75	2.91	76.7	27.3	104.0	1.419	6.36	.801
*		7	1300	17.5		143	209	66	24.80	16.5	139	.01080	.000863	.08	31	89	31	.216	.250	6.13	5.47	74.4	26.8	101.2	1.079	6.06	.640
F = .08 4/29/47		8	1300	17.2		142	211	66	26.22	15.2	140	.01078	.000864	.08	31	89	0	0	0	6.20	3.92	73.0	27.1	100.1	.864	6.14	.507

*Runs made 4/5/47
Bar. 30.270"Hg

Note:
Runs made on 4/29/47 used new water rotameter

EXPERIMENT NO. ____ TITLE *Water Injection* DATE *4/5/47* SLOAN LABORATORY

ENGINE *CFR 9-B* FUEL *73 Octane* S.G. *.719* WET BULB ____ DRY BULB *74°F*

BORE *3.25"* STROKE *4.50"* COMPRESSION RATIO *7.0* BAROMETER (ACT.) *771.5 mm Hg* (CORR.) *30.270" Hg*

CONSTANTS BMEP = B.L. X ____ BHP = $\frac{\text{B.L. X RPM}}{}$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_I	P_E	T_I	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto	Water Roto	Water Cons	$\frac{W_w}{W_f}$	Orifice Δp	P_i Δp	Bmep	Fmep	Imep	Liquid Cons	IHP	Isfc
				"Hg		°F	°F	psi	"Hg	"H_2O	°F	lbs/sec	lbs/sec		°BTC			$\times 10^{-3}$ lbs/sec		"H_2O	"Hg	psia	psia	psia	$\times 10^{3}$ lbs/sec		lbs. Liq / IHP-hr
	1545	1	1300	11.00		142	207	64	19.72	16.2	139	.00827	.000498	.06	31	70.0	0	0	0	3.62	10.55	46.6	25.70	72.3	.498	4.43	.404
	1550	2	1300	12.90		142	208	64	21.30	16.3	140	.00900	.000540	.06	31	72.0	35	.285	.528	4.25	8.97	54.7	26.00	80.7	.825	4.94	.601
	1600	3	1300	14.60		142	206	64	24.13	16.4	139	.01020	.000612	.06	31	76.0	117	.777	1.27	5.46	6.14	62.0	26.50	885	1.389	5.42	.920
	1605	4	1300	15.40		142	208	64	25.43	16.5	140	.01082	.000650	.06	31	78.0	148	1.065	1.64	6.17	4.84	66.2	26.90	931	1.715	5.71	1.080
	1620	5	1300	16.30		142	208	65	26.81	16.7	140	.01146	.000688	.06	31	80.0	170	1.285	1.87	6.95	3.46	69.2	27.20	96.4	1.973	5.90	1.205
	1630	6	1300	16.40		142	208	65	28.11	16.9	139	.01213	.000728	.06	31	82.0	178	1.367	1.88	7.70	2.16	69.6	27.50	97.1	2.095	5.95	1.270
	1420	1	1300	19.0		141	208	66	27.63	16.8	140	.01180	.000826	.07	31	87.0	222	1.875	2.27	7.35	2.64	80.6	28.0	108.6	2.701	6.65	1.460
	1430	2	1300	17.9		140	208	66	26.57	16.7	140	.01122	.000786	.07	31	85.0	209	1.712	2.18	6.65	3.70	76.0	27.8	103.8	2.498	6.36	1.410
	1440	3	1300	16.7		141	209	64	25.35	16.6	142	.01068	.000747	.07	31	83.0	188	1.473	1.97	5.99	4.92	71.0	27.5	98.5	2.220	6.03	1.325
	1455	4	1300	15.8		140	207	64	24.13	16.6	142	.01019	.000708	.07	31	81.0	164	1.125	1.59	5.40	6.14	67.0	27.2	94.2	1.833	5.76	1.150
	1505	5	1300	14.9		140	209	64	22.99	16.5	140	.00958	.000670	.07	31	79.0	112	.733	1.093	4.89	7.28	63.2	26.9	90.1	1.403	5.62	.917
	1515	6	1300	13.8		141	208	64	21.65	16.4	140	.00904	.000632	.07	31	77.0	65	.387	.612	4.30	8.62	58.5	26.6	85.1	1.019	5.21	.704
	1525	7	1300	12.8		141	206	64	20.18	16.3	138	.00846	.000593	.07	31	75.0	0	0	0	3.78	10.09	54.4	26.2	80.6	.593	4.94	.432
	1245	1	1300	19.3		141	208	66	27.87	16.8	142	.01180	.000946	.08	31	93.5	212	1.75	1.850	7.35	2.40	82.0	28.1	110.1	2.696	6.75	1.435
	1250	2	1300	18.7		141	207	66	27.28	16.8	140	.01150	.000920	.08	31	92.0	203	1.642	1.785	7.00	2.99	79.4	27.9	107.3	2.562	6.58	1.400
	1300	3	1300	18.0		140	207	65	26.26	16.7	140	.01104	.000884	.08	31	90.0	182	1.409	1.590	6.46	4.01	76.3	27.7	104.0	2.293	6.37	1.290
COURSE	1305	4	1300	17.0		140	207	66	25.19	16.6	142	.01054	.000844	.08	31	88.0	157	1.154	1.370	5.91	5.08	72.1	27.4	99.5	1.998	6.10	1.180
GROUP	1315	5	1300	15.7		141	208	65	23.70	16.5	142	.00994	.000796	.08	31	85.5	115	.760	.955	5.24	6.57	66.6	27.1	93.7	1.556	5.74	.975
NAMES	1320	6	1300	14.8		141	210	65	22.20	16.4	140	.00933	.000747	.08	31	83.0	38	.249	.333	4.65	8.07	62.9	26.7	89.6	.996	5.49	.654
	1330	7	1300	14.0		141	210	65	21.29	16.3	138	.00904	.000724	.08	31	82.0	0	0	0	4.33	8.98	59.4	26.4	85.8	.724	5.25	.496

EXPERIMENT NO. ____ TITLE *Alcohol Injection* ____ DATE *4/17/47* ____ SLOAN LABORATORY

ENGINE *CFR 9-B* ____ FUEL *73 Octane* ____ S.G. *.719* ____ WET BULB ____ DRY BULB *73°F*

BORE *3.25"* STROKE *4.50"* COMPRESSION RATIO *7.0* ____ BAROMETER (ACT.) *759.1 mm Hg.* (CORR.) *29.766" Hg*

CONSTANTS BMEP = B.L. X *4.245* BHP = $\frac{\text{B.L. x RPM}}{\quad}$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto	Alc Roto	Alc Cons.	$\frac{W_{ac}}{W_f}$	Orifice ΔP	p_i ΔP	Bmep	Fmep	Imep	Liq Cons	IHP	Isfc
				"Hg		°F	°F	psi	"Hg	"H_2O	°F	lbs/sec	lbs/sec		°BTC			x10⁻³ lbs/sec		"H_2O	"Hg	psia	psia	psia	x10⁻³ lbs/sec		lbs Liq / IHP-hr
	1340	1	1300	22.1		142	205	67	28.57	15.6	136	.01257	.000755	.06	31	83.5	136	1.252	1.66	8.5	1.2	93.9	28.3	122.2	2.007	7.50	.964
	1345	2	1300	21.3		142	212	67	27.87	15.6	138	.01220	.000731	.06	31	82	133	1.200	1.64	8.0	1.9	90.5	28.1	118.6	1.931	7.36	.945
	1350	3	1300	20.2		142	207	66	26.77	15.5	138	.01158	.000673	.06	31	80	119	.962	1.39	7.2	3.0	85.8	27.8	113.6	1.655	6.96	.856
	1355	4	1300	19.0		141	211	66	25.37	15.3	140	.01090	.000654	.06	31	78	100	.674	1.03	6.4	4.4	80.6	27.45	108.05	1.328	6.62	.722
	1400	5	1300	17.5		141	211	66	23.87	15.3	142	.01020	.000612	.06	31	76	69	.317	.518	5.6	5.9	74.3	27.10	101.4	.929	6.21	.539
	1405	6	1300	15.4		141	211	66	22.17	15.2	143	.00945	.000565	.06	31	73.5	58.5	.234	.414	4.8	7.6	65.4	26.70	92.1	.799	5.65	.509
	1410	7	1300	12.7		141	211	66	20.07	15.1	142	.00862	.000517	.06	31	71.0	12.0	.035	.0676	4.0	9.7	53.9	26.20	80.1	.552	4.91	.405
	1420	8	1300	11.1		141	211	66	18.98	15.0	143	.00795	.000477	.06	31	68.5	0	0	0	3.4	10.8	47.1	25.90	73.0	.477	4.47	.388
	1430	1	1300	22.1		140	211	66	28.27	15.6	138	.01257	.000880	.07	31	90.0	125	1.062	1.210	8.5	1.5	93.90	28.20	122.10	1.942	7.49	.935
	1440	2	1300	20.9		140	211	66	27.27	15.6	137	.01197	.000837	.07	31	87.5	114	.884	1.055	7.7	2.5	88.75	27.95	116.70	1.721	7.15	.869
	1450	3	1300	19.9		139	210	66	26.07	15.5	138	.01133	.000794	.07	31	85.5	87	.503	.634	6.9	3.7	84.50	27.60	112.10	1.297	6.88	.679
	1500	4	1300	18.2		139	211	66	24.57	15.4	138	.01064	.000746	.07	31	83.0	64	.274	.367	6.1	5.2	77.25	27.30	104.55	1.020	6.35	.580
	1505	5	1300	16.5		139	211	66	22.87	15.3	139	.00992	.000695	.07	31	80.5	47	.158	.2275	5.3	6.9	70.00	26.90	96.90	.853	5.94	.518
	1510	6	1300	14.5		141	212	66	21.37	15.1	140	.00915	.000641	.07	31	77.5	12	.035	.0546	4.5	8.4	61.50	26.50	88.00	.676	5.39	.451
	1515	7	1300	13.9		141	211	66	20.97	15.1	140	.00894	.000626	.07	31	77.0	0	0	0	4.3	8.8	59.00	26.40	85.40	.626	5.22	.432
	1530	1	1300	22.0		142	212	66	28.57	15.7	139	.01257	.001004	.08	31	96.5	120	.978	.975	8.5	1.2	93.4	28.2	121.6	1.982	7.45	.958
COURSE	1540	2	1300	20.8		142	212	66	27.37	15.7	140	.01197	.000955	.08	31	94.0	101.5	.695	.728	7.7	2.4	88.3	28.0	116.3	1.650	7.14	.833
GROUP	1545	3	1300	19.6		142	212	66	25.97	15.5	140	.01133	.000905	.08	31	91.0	69	.317	.350	6.9	3.8	83.2	27.6	110.8	1.222	6.79	.649
NAMES	1550	4	1300	17.9		142	207	66	24.57	15.4	140	.01064	.000850	.08	31	88.5	50	.177	.208	6.1	5.2	76.0	27.3	103.3	1.027	6.34	.584
	1555	5	1300	15.9		143	207	66	23.01	15.3	141	.00992	.000772	.08	31	85.5	14	.037	.0467	5.3	6.7	67.5	26.9	94.4	.829	5.78	.515
	1600	6	1300	15.2		143	207	66	22.37	15.2	142	.00955	.000762	.08	31	84.0	0	0	0	4.9	7.4	64.5	26.7	91.2	.762	5.59	.492

EXPERIMENT NO. ____ TITLE *Water Injection* DATE *4/8/47* SLOAN LABORATORY

ENGINE *CFR 9-B* FUEL *73 Octane* S.G. *.719* WET BULB *—* DRY BULB *74°F*

BORE *3.25*" STROKE *4.50*" COMPRESSION RATIO *8.0* BAROMETER (ACT.) *770.7 mm Hg.* (CORR.) *30.227 "Hg.*

CONSTANTS BMEP = B.L. X BHP = $\frac{\text{B.L. X RPM}}{}$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto	Water Roto	Water Cons.	$\frac{W_w}{W_F}$	Orifice ΔP	P_i ΔP	BMEP	FMEP	IMEP	Liq. Cons.	IHP	islc
				"Hg		°F	°F	psi	"Hg.	"H_2O	°F	lbs/sec	lbs/sec.		°BTC			lbs/sec $\times 10^{-3}$		"H_2O	"Hg.	psia	psia.	psia	lbs/sec $\times 10^{-3}$		lbs/IHP hr
	1540	1	1300	8.2		141	210	64	16.61	15.8	140	.00891	.000415	.06	31	65	0	0	0	2.52	13.62	34.8	26.0	60.8	.415	3.72	.402
	1545	2	"	9.7		138	210	62	18.03	15.8	138	.00750	.000450	"	"	67	16	.158	.351	2.95	12.20	41.2	26.3	67.5	.608	4.14	.530
	1555	3	"	11.0		143	210	62	19.53	15.8	140	.00807	.000485	"	"	69	74	.452	.932	3.42	10.70	46.7	26.7	73.4	.937	4.49	.752
	1600	4	"	12.1		143	208	63	21.02	15.9	140	.00863	.000518	"	"	71	98	.633	1.222	3.93	9.21	51.4	27.0	78.4	1.151	4.80	.819
	1605	5	"	13.0		142	208	61	22.36	16.0	138	.00926	.000556	"	"	73	136	.985	1.770	4.52	7.87	55.2	27.4	82.6	1.541	5.06	1.095
	1610	6	"	14.8		141	211	62	23.74	16.0	140	.00988	.000593	"	"	75	151	1.147	1.930	5.15	6.49	62.8	27.7	90.5	1.740	5.54	1.130
	1615	7	"	15.9		141	211	61	25.19	16.1	140	.01050	.000631	"	"	77	176	1.412	2.241	5.82	5.04	67.5	28.0	95.5	2.043	5.85	1.260
	1620	8	"	17.2		141	211	62	26.68	16.1	140	.01113	.000669	"	"	79	190	1.567	2.340	6.54	3.85	73.0	28.3	101.3	2.236	6.21	1.295
	1225	1	"	16.5		140	210	65	24.17	16.7	140	.01050	.000736	.07	"	82.5	225	1.835	2.490	5.83	5.06	70.0	27.8	97.8	2.571	5.99	1.545
	1235	2	"	15.5		140	210	65	23.86	16.7	140	.00983	.000688	"	"	80	195	1.587	2.300	5.08	6.37	65.8	27.7	93.5	2.275	5.72	1.430
	1240	3	"	14.5		141	210	65	22.51	16.6	140	.00929	.000650	"	"	78	169	1.305	2.010	4.56	7.66	61.5	27.4	88.9	1.955	5.44	1.295
	1245	4	"	13.4		140	211	65	21.08	16.4	140	.00875	.000612	"	"	76	134	.947	1.548	4.01	9.15	56.9	27.0	83.9	1.559	5.13	1.090
	1250	5	"	12.3		140	209	65	19.84	16.4	140	.00822	.000575	"	"	74	97	.616	1.071	3.54	10.39	52.2	26.7	78.9	1.191	4.82	.890
	1300	6	"	11.3		141	211	62	18.73	16.3	141	.00770	.000539	"	"	72	56	.345	.640	3.11	11.50	48.0	26.5	74.5	.884	4.56	.698
	1100	1	"	11.8		144	208	65	18.81	16.3	140	.00796	.000637	.08	"	77.5	0	0	0	3.35	11.42	50.1	26.5	76.6	.637	4.70	.488
	1115	2	"	12.8		141	210	65	20.03	16.3	140	.00835	.000668	"	"	79	57	.356	.533	3.70	10.20	54.3	26.8	81.1	1.024	4.96	.744
COURSE	1125	3	"	13.9		141	210	65	21.23	16.4	140	.00885	.000708	"	"	81	102	.658	.930	4.14	9.00	59.0	27.2	86.2	1.366	5.28	.931
GROUP	1135	4	"	14.5		141	210	65	22.45	16.5	139	.00935	.000747	"	"	83	164	1.259	1.683	4.60	7.78	61.5	27.4	88.9	2.006	5.44	1.325
NAMES	1145	5	"	15.4		141	210	65	23.63	16.5	140	.00983	.000786	"	"	85	205	1.707	2.170	5.12	6.60	65.4	27.7	93.1	2.493	5.70	1.570

EXPERIMENT NO. ____ TITLE *Alcohol Injection* DATE *4/22/47* SLOAN LABORATORY

ENGINE *CFR 9-B* FUEL *73 Octane* S.G. *.719* WET BULB *—* DRY BULB *76°F*

BORE *3.25"* STROKE *4.50"* COMPRESSION RATIO *8.0* BAROMETER (ACT.) *766.7 mm. Hg.* (CORR.) *30.078" Hg.*

CONSTANTS BMEP = B.L. X *4.245* BHP = $\frac{\text{B.L. x RPM}}{}$

REMARKS	TIME	RUN	RPM	B.L.	F.L.	TEMP. OIL	TEMP. JAC	OIL PRES.	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	$\frac{F}{A}$	S.A.	Fuel Roto	Alc. Roto	Alc. Cons.	$\frac{W_{alc}}{W_f}$	Orifice ΔP	P_i ΔP	BMEP	FMEP	IMEP	Liq. Cons.	IHP	isfc
				"Hg		°F	°F	psi	"Hg	"H_2O	°F	lbs./sec.	lbs./sec.		°BTC			lbs./sec $\times 10^{-3}$		"H_2O	"Hg	psia	psia	psia	lbs./sec $\times 10^{-3}$		lbs/IHP hr.
	1245	1	1300	20.0		142	212	66	26.83	15.8	138	.01152	.000691	.06	31	80	155	1.598	2.31	7.04	3.25	84.9	28.5	113.4	2.289	8.20	1.185
	1250	2	"	18.4		142	205	66	25.66	15.7	140	.01086	.000650	"	"	78	149	1.487	2.28	6.25	4.42	78.0	28.1	106.1	2.137	6.50	1.180
	1255	3	"	17.2		142	211	66	24.27	15.5	140	.01022	.000612	"	"	76	139	1.305	2.13	5.54	5.81	73.0	27.8	100.8	1.917	6.16	1.119
	1300	4	"	16.1		142	211	66	23.10	15.4	144	.00962	.000576	"	"	74	126	1.078	1.87	4.90	6.98	68.4	27.5	95.9	1.654	5.86	1.015
	1305	5	"	14.8		140	208	66	21.56	15.3	142	.00900	.000539	"	"	72	107	.776	1.44	4.29	8.52	62.8	27.1	89.9	1.315	5.50	.860
	1310	6	"	13.5		140	211	66	20.18	15.2	141	.00837	.000502	"	"	70	61	.252	.502	3.73	9.90	57.3	26.8	84.1	.754	5.15	.527
	1315	7	"	12.1		140	211	66	18.86	15.1	140	.00779	.000467	"	"	68	52	.189	.405	3.22	11.22	51.4	26.5	77.9	.656	4.77	.495
	1320	8	"	14.2		142	208	66	20.74	15.2	139	.00864	.000518	"	"	71	77	.394	.761	3.95	9.34	60.2	26.9	87.1	.912	5.34	.614
	1325	9	"	10.9		140	210	66	18.16	15.0	138	.00751	.000450	"	"	67	40	.129	.286	3.00	11.92	46.2	26.3	72.5	.579	4.44	.469
	1330	10	"	9.6		140	211	66	17.65	15.0	140	.00722	.000433	"	"	66	20	.047	.108	2.76	12.43	40.7	26.2	66.9	.480	4.10	.358
	1340	11	"	8.0		140	211	67	15.86	15.0	140	.00635	.000380	"	"	62.5	0	0	0	2.14	14.22	33.9	25.7	59.6	.380	3.66	.374
	1515	1	"	22.3		140	206	67	28.98	16.0	136	.01249	.000874	.07	"	89.5	156	1.615	1.85	8.25	1.10	94.5	29.0	123.5	2.989	7.56	1.185
	1525	2	"	19.0		140	211	67	25.81	16.0	140	.01094	.000767	"	"	84	132	1.182	1.54	6.37	4.27	80.6	28.2	108.8	1.949	6.65	1.054
	1530	3	"	17.3		140	211	67	24.04	15.8	141	.01010	.000708	"	"	81	108	.791	1.12	5.42	6.04	73.4	27.8	101.2	1.499	6.20	.870
	1535	4	"	15.6		140	211	67	22.23	15.4	141	.00928	.000650	"	"	78	83	.458	.705	4.57	7.85	66.2	27.3	93.2	1.108	5.72	.698
	1540	5	"	19.5		140	211	67	26.40	15.8	140	.01121	.000786	"	"	85	138	1.287	1.635	6.67	3.68	82.6	28.3	110.9	2.073	6.79	1.100
	1545	6	"	13.8		140	211	67	20.28	15.3	140	.00848	.000594	"	"	75	52	.189	.318	3.82	9.80	58.5	26.8	85.3	.785	5.22	.540
COURSE	1550	7	"	11.7		140	211	67	18.63	15.2	142	.00770	.000539	"	"	72	29	.072	.134	3.12	11.45	49.6	26.5	76.1	.611	4.66	.472
GROUP																											
NAMES	1600	1	"	22.0		144	210	66	29.98	16.0	138	.01242	.000994	.08	"	96	151	1.524	1.532	8.20	1.10	93.4	29.0	122.4	2.518	7.50	1.205
	1605	2	"	20.4		142	204	66	27.28	16.0	138	.01173	.000939	"	"	93	138	1.287	1.371	7.30	2.60	86.4	28.5	114.9	2.226	7.04	1.140
	1610	3	"	18.7		142	211	67	25.30	15.7	138	.01079	.000862	"	"	90	106	.761	.884	6.18	4.78	79.3	28.0	107.3	1.623	6.57	.892
	1615	4	"	17.8		141	212	66	24.36	15.7	138	.01031	.000825	"	"	87	85	.480	.582	5.65	5.72	75.5	27.8	103.3	1.305	6.34	.742
	1620	5	"	16.1		141	205	66	22.77	15.5	139	.00960	.000767	"	"	84	60	.245	.320	4.89	7.31	68.3	27.5	95.8	1.012	5.86	.621
	1625	6	"	14.2		140	210	67	20.98	15.2	140	.00885	.000708	"	"	81	36	.101	.143	4.16	9.10	60.2	27.0	87.2	.809	5.34	.545

XII - APPENDIX - a

After all the data for the water and alcohol injection had been correlated, and the great advantage of alcohol over water was evident from the standpoint of raising the detonation limited IMEP, the thought occurred of trying to inject fuel in the same manner and for the same purpose. On 17 May 1947 a run was made at a compression ratio of 7 and F/A ratio of .07 using 73 octane gasoline as the injected fluid. A series of points was taken and a very favorable comparison obtained of fuel vs. alcohol as an anti-detonator. A thorough investigation of this method of detonation control would be of extreme interest and might lead to results more practical than the use of ethyl alcohol. Certainly the use of one fluid rather than two would facilitate the supply problem and lend itself to a lighter installation; from this standpoint the ideal system would be one in which a single pump would deliver both the primary fuel and the anti-detonating fuel at their optimum timing and through a single line to each cylinder.

XII - APPENDIX - b

Procedure for Operating C.F.R. Engines

Sloan Laboratory

(1) Preparation:

(a) Start laboratory gasoline pump.
(b) Start laboratory exhaust pump.
(c) Start laboratory trench pump.
(d) Lock dynamometer cradle.
(e) Check oil level in engine crankcase.
(f) Open fuel valve to engine.
(g) Shut engine fuel pump.
(h) Open engine ignition switch.
(i) Open valve to laboratory main exhaust line.*
(j) Open throttle valve on engine.

(2) Motoring:

(a) Fill engine jacket.
(b) Start circulating-water pump.
(c) Open condenser-coil valve.
(d) Open exhaust cooling-water valve.
(e) Close dynamometer main switch.
(f) Turn field rheostats fully counter-clockwise.
(g) Close field switch.
(h) Close armature switch.
(i) Motor the engine by gradually advancing the starter switch.
(j) Check oil pressure.
(k) To adjust rpm after motoring, turn field rheostats.

(3) Firing

(a) Adjust inlet-air temperature to 100°F.
(b) Read air consumption.
(c) Open engine fuel pump. Read fuel consumption. Adjust micrometer to give fuel-air ratio of 0.08 - 0.10 (approx.).
(d) Close engine-ignition switch.
(e) To adjust rpm after firing, turn field rheostats.
(f) To adjust fuel-air ratio, turn fuel pump micrometer.

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*Check with all research projects to see if laboratory exhaust and supercharger mains are free for use.

(4) <u>Changing Compression Ratio when Engine is Firing</u>:

(a) Unlock cylinder-head <u>slightly</u>.
(b) Turn handle clockwise to decrease compression ratio. Turn handle counter-clockwise to increase compression ratio.
(c) Check the desired compression ratio with calibration chart.
(d) Lock cylinder head.

(5) <u>Stopping</u>:

(a) Lock dynamometer cradle.
(b) Adjust to a reasonably low rpm.
(c) Open engine ignition switch.
(d) Shut engine fuel pump.
(e) Close all water valves (<u>important</u>).
(f) Stop circulating water pump.
(g) Close fuel valve to engine.
(h) Open armature switch.
(i) Open field switch.
(j) Open dynamometer main switch.
(k) Close valve to laboratory main exhaust line.
(l) If no other group is operating engine in the laboratory, close laboratory gasoline pump, exhaust pump and trench pump.

(6) <u>Emergency</u>:

In case of emergency, cut off ignition switch of the engine <u>first</u>. Then follow through the rest of stopping procedure.

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